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The Long-Term Effect of ABS in Passenger Cars and LTVs

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16. Abstract

Statistical analyses based on data for calendar years 1995 to 2007 from the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES) of the National Automotive Sampling System (NASS) estimate the long-term effectiveness of antilock brake systems (ABS) for passenger cars and LTVs (light trucks and vans) subsequent to the 1995 launch of public information programs on how to use ABS correctly. ABS has close to a zero net effect on fatal crash involvements. Fatal run-off-road crashes of passenger cars increased by a statistically significant 9 percent (90% confidence bounds: 3% to 15% increase), offset by a significant 13-percent reduction in fatal collisions with pedestrians (confidence bounds: 5% to 20%) and a significant 12-percent reduction in collisions with other vehicles on wet roads (confidence bounds: 3% to 20%). ABS is quite effective in nonfatal crashes, reducing the overall crash-involvement rate by 6 percent in passenger cars (confidence bounds: 4% to 8%) and by 8 percent in LTVs (confidence bounds: 3% to 11%). The combination of electronic stability control (ESC) and ABS will prevent a large proportion of fatal and nonfatal crashes.

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LIST OF ABBREVIATIONS

ABS	Antilock brake system
AIS	Abbreviated Injury Scale
ANPRM	Advance Notice of Proposed Rulemaking
BAC	Blood alcohol concentration, measured in grams per deciliter (g/dL)
BMW	Bayerische Motoren Werke
CY	Calendar Year
df	Degrees of Freedom
DOT	United States Department of Transportation
ESC	Electronic Stability Control
FARS	Fatality Analysis Reporting System, a census of fatal crashes in the United States since 1975
FMVSS	Federal Motor Vehicle Safety Standard
GDP	Gross Domestic Product
GES	General Estimates System of NASS
GM	General Motors
GVWR	Gross vehicle weight rating, specified by the manufacturer, equals the vehicle's curb weight plus maximum recommended loading
IIHS	Insurance Institute for Highway Safety
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
LTV	Light Trucks and Vans, includes pickup trucks, SUVs, minivans, and full-size vans
MY	Model year
NASS	National Automotive Sampling System, a probability sample of police-reported crashes in the United States since 1979, investigated in detail
NHTSA	National Highway Traffic Safety Administration

NPRM	Notice of Proposed Rulemaking
OMB	Office of Management and Budget of the United States Government
Pct Pt	Percentage Point
PSU	Primary Sampling Unit
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, 2005
SAS	Statistical and database management software produced by SAS Institute, Inc.
SUV	Sport utility vehicle
VIN	Vehicle Identification Number
VMT	Vehicle miles of travel
VW	Volkswagen

EXECUTIVE SUMMARY

Antilock brake systems (ABS) have close to a zero net effect on fatal crash involvements. Run-off-road crashes significantly increase, offset by significant reductions in collisions with pedestrians and collisions with other vehicles on wet roads. But ABS is quite effective in nonfatal crashes, reducing the overall crash-involvement rate by 6 percent in passenger cars and by 8 percent in LTVs (light trucks – including pickup trucks and SUVs – and vans). In a few years all new vehicles will be equipped with electronic stability control and will almost certainly also be equipped with ABS. The combination of ESC and ABS will prevent a large proportion of fatal and nonfatal crashes.

The fundamental safety problem addressed by four-wheel ABS is that, in an emergency situation, the average driver brakes too hard, locking the wheels, which causes the vehicle to lose directional control. If the front wheels lock, the vehicle will continue in a straight path, but the driver will be unable to steer it. If the rear wheels lock, the vehicle can spin out and lose control. ABS senses if any of the four wheels is about to lock, and if so, it quickly releases the brakes on that wheel. Cycles of releasing, holding, and reapplying brakes are repeated many times per second. As long as the driver maintains firm pressure on the brake pedal, ABS automatically provides optimum braking force short of lockup. ABS enables the driver to steer while braking, prevents yawing due to rear-wheel lockup, and on many surfaces reduces stopping distances relative to a skidding vehicle.

Federal Motor Vehicle Safety Standard No. 126 will require all new passenger vehicles to be equipped with ESC, a remarkably effective crash-avoidance technology, after September 1, 2011. All ESC systems to date and for the foreseeable future incorporate ABS technology. The ESC standard will apparently soon place ABS on every new car and LTV sold in the United States.

Numerous stopping tests by expert drivers at test tracks showed that four-wheel ABS is successful, especially on wet pavements, in improving overall vehicle stability during braking, preserving the ability to steer, and reducing stopping distances on many surfaces. But previous statistical evaluations of ABS have had ambiguous results. Analyses of data from the early 1990s showed significant increases in fatal run-off-road crashes with ABS, on the order of 28 percent. The increase was baffling, given the success of ABS on the test track. However, at that time, many drivers did not yet know how to use ABS correctly. During the mid-1990s, the safety community worked hard to inform the public about the correct use of ABS ("Don't let up on the brakes"; "Stomp, stay, and steer"). A second generation of analyses circa 2000 showed much smaller increases in run-off-road crashes that were no longer statistically significant. But they were based on just two or three years of data and left uncertainty about the overall effect of ABS.

It is time for a new evaluation of ABS, including the crash data that has accumulated over the past decade and in view of the fact that all new cars and LTVs will likely soon be equipped with ABS along with ESC. The analyses are based on data for calendar years 1995 to 2007 from the Fatality Analysis Reporting System and the General Estimates System (GES) of the National Automotive Sampling System; 1995 was the launch of major public-information programs about

ABS. The goal is to estimate the long-term effect of ABS. Data up to 2007 comprises most of the later service life of the makes and models that were originally equipped with ABS. It also allows inclusion of models that received ABS more recently, and even some models that once had standard ABS and subsequently just optional ABS.

The following table displays the principal statistical findings of this evaluation – namely, the estimated percentage reductions in crash involvements for cars or LTVs equipped with four-wheel ABS relative to comparable cars or LTVs not equipped with any ABS. Positive estimates (reductions in crash involvements with ABS) are shown in black, negative estimates in red. Statistically significant estimates (at the one-sided .05 level) are printed bold, and they are shaded light blue if positive, yellow if negative.

ESTIMATED CRASH REDUCTION (%) BY FOUR-WHEEL ABS, 1995-2007

	All Roads		Wet, Snowy, or Icy Roads	
	Cars	**LTVs**	**Cars**	**LTVs**
FATAL CRASH INVOLVEMENTS				
All fatal involvements	1	- 1	- 1	- 6
All run-off-road crashes	**- 9**	- 6	**- 34**	- 10
Side impacts with fixed objects	**- 30**	none	**- 85**	- 4
First-event rollovers	- 11	- 10	**- 52**	**- 31**
All other run-off-road crashes	- 3	- 5	**- 17**	- 3
Pedestrian/bicyclist/animal	**13**	**14**	none	- 14
Culpable involvements w other veh	4	- 1	**12**	- 6
ALL CRASH INVOLVEMENTS				
All crash involvements	**6**	**8**	**16**	**14**
All run-off-road crashes	- 1	11	- 13	3
Side impacts with fixed objects	**- 20**	- 9	**- 43**	- 15
First-event rollovers	3	17	- 12	6
All other run-off-road crashes	5	15	- 3	9
Pedestrian/bicyclist/animal	- 8	**- 42**	- 8	- 10
Culpable involvements w other veh	**17**	**20**	**37**	**36**

- The long-term overall effect of ABS on fatal crash involvements is close to zero in both cars and LTVs. The observed effect in cars is a 1-percent reduction (90% confidence bounds range from a 2% increase to a 4% reduction). The observed effect in LTVs is a 1-percent increase (confidence bounds: -6% to 4%).

- But the overall effect of ABS on all crash involvements, including nonfatal involvements is beneficial and statistically significant in both cars and LTVs. The observed reductions are 6 percent in cars (confidence bounds: 4% to 8%) and 8 percent in LTVs (confidence bounds: 3% to 11%).

- The overall reduction of nonfatal-injury crashes is approximately the same as the reduction of all crashes.[1]

- Fatal run-off-road crashes increase with ABS by a statistically significant 9 percent in cars (confidence bounds: 3% to 15% increase). The long-term effect is substantially smaller than in the early years of ABS (28% increase), but it is still a significant increase. The observed effect in LTVs is a non-significant 6-percent increase (confidence bounds: -16% to 3%).

- On wet, snowy, or icy roads, where ABS is most likely to activate, the increase in fatal run-off-road crashes is a statistically significant 34 percent in passenger cars (confidence bounds: 20% to 50% increase). On these roads, all three types of fatal run-off-road crashes increase significantly for cars and so do fatal rollovers of LTVs.

- On dry roads, the increase in fatal run-off-road crashes is a non-significant 4 percent in passenger cars.

- Side impacts with fixed objects generally increase even more with ABS than other types of run-off-road crashes (except for LTV fatalities). Fatal and nonfatal crashes both increase significantly for passenger cars.

- The statistical analyses continue to show persistent, significant increases in run-off-road crashes with ABS, especially on wet roads. They remain at odds with the impressive performance of ABS on the test track, especially on wet roads. They do not tally with the benefits of ABS observed in other types of crashes. We are still unable to provide a convincing explanation or empirical evidence (other than the crash statistics themselves) for the increase in run-off-road crashes.

- Fatal collisions with pedestrians, bicyclists, or animals decrease significantly, overall, with ABS. The observed reductions are 13 percent in cars (confidence bounds: 5% to 20%) and 14 percent in LTVs (confidence bounds: 3% to 25%). But the observed effects on wet, snowy, or icy roads are not positive.

- Culpable fatal involvements with other vehicles on wet, snowy, or icy roads were reduced by a statistically significant 12 percent in passenger cars (confidence bounds: 3% to 20%).

[1] Not shown in the table on the preceding page.

- Culpable involvements with other vehicles on all roads decreased significantly in cars and LTVs. The observed reductions are 17 percent in cars (confidence bounds: 13% to 22%) and 20 percent in LTVs (confidence bounds: 12% to 28%).

- The effects on culpable involvements with other vehicles on wet, snowy or icy roads are a remarkable 37 percent reduction in cars (confidence bounds: 29% to 45%) and 36 percent in LTVs (confidence bounds: 24% to 46%). ABS is highly effective here.

Although the preceding analyses show a significant 9-percent increase for ABS on run-off-road crashes of passenger cars, the increase is small relative to the likely benefits of ESC. NHTSA's 2007 evaluation of ESC, based on statistical analyses through calendar year 2004, found a 36-percent reduction in fatal run-off-road crashes. Thus, the combined effect of ESC and ABS is an estimated 30-percent reduction of fatal crashes.[2]

The following table estimates the combined effects of four-wheel ABS and ESC. The estimates for ABS are from this evaluation; the ESC numbers are from NHTSA's 2007 evaluation and estimate the effect on ESC on a vehicle that had previously been equipped with ABS. (A caveat: these are still somewhat early estimates of ESC effectiveness; NHTSA plans follow-up statistical analyses to estimate the long-term effectiveness of ESC.)

- The combined effects are all substantial reductions.

- Negative effects of ABS on run-off-road crashes – whatever may be causing them – are possibly remedied and in any case dwarfed by the likely benefits of ESC.

- The combined effects on culpable involvements with other vehicles, where ABS is especially effective, are large.

[2] Dang (2007); 1 - [(1 + .09) x (1 - .36)] = 30% reduction.

ESTIMATED CRASH REDUCTION (%) FOR FOUR-WHEEL ABS PLUS ESC

	Four-Wheel ABS	ESC	Combined
FATAL CRASH INVOLVEMENTS			
Passenger cars			
All fatal involvements	1	14	15
All run-off-road crashes	– 9	36	30
Culpable involvements w other veh	4	19	22
LTVs			
All fatal involvements	– 1	28	27
All run-off-road crashes	– 6	70	68
Culpable involvements w other veh	– 1	34	33
ALL CRASH INVOLVEMENTS			
Passenger cars			
All crash involvements	6	8	14
All run-off-road crashes	– 1	45	44
Culpable involvements w other veh	17	13	28
LTVs			
All crash involvements	8	10	17
All run-off-road crashes	11	72	75
Culpable involvements w other veh	20	16	3

CHAPTER 1

HISTORY OF ABS AND PREVIOUS EFFECTIVENESS FINDINGS

1.1 Rationale for ABS

The fundamental safety problem addressed by antilock braking systems is that few drivers are able to modulate pressure on the brake pedal optimally in a sudden emergency situation or on an unexpectedly slippery surface. The average driver will either brake timidly, lengthening stopping distance, or brake too hard, locking the wheels. If excess pedal pressure locks only the front wheels, the vehicle will continue in a straight path, but the driver will be unable to steer it and avoid obstacles. If it locks the rear wheels, the vehicle can spin out and lose control.

Four-wheel ABS senses if any of the four wheels is about to lock, and if so, it quickly releases the brakes on that wheel and lets it start rolling again. Cycles of releasing, holding and reapplying brakes are repeated many times per second. As long as the driver maintains firm pressure on the brake pedal, ABS will automatically modulate the pressure at the wheels at a level close to the optimum braking force short of lockup. ABS will enable the driver to steer while braking, prevent yawing due to rear-wheel lockup, and on many surfaces reduce stopping distances relative to a skidding vehicle.[3]

Light trucks and vans – including pickup trucks, sport utility vehicles, minivans, and full-size vans with a GVWR less than 10,000 pounds – are especially prone to rear-wheel lockup when they are not heavily loaded, and especially crash-prone once they yaw out of control. Many LTVs, including all domestic pickup trucks, were equipped with rear-wheel-only ABS for several model years before they received four-wheel ABS. This system senses if any of the rear wheels is about to lock and if so, it quickly releases the brakes on that wheel and lets it start rolling again. Rear-wheel ABS, however, does not prevent front-wheel lockup or assure steering control during braking. If the front wheels lock while the rear wheels turn, the truck will usually just slow down in a straight line, without yawing.

The preceding are good reasons why drivers might want ABS on their vehicles. But now a compelling rationale has developed for equipping all new vehicles with ABS. Federal Motor Vehicle Safety Standard No. 126 will require all new passenger vehicles to be equipped with electronic stability control after September 1, 2011. ESC is a remarkably effective crash-avoidance technology.[4] However, all ESC systems to date and for the foreseeable future incorporate ABS technology. The ESC standard will apparently soon place ABS on every new car and LTV sold in the United States.

[3] Kahane, C. J. (2004). *Lives Saved by the Federal Motor Vehicle Safety Standards and Other Vehicle Safety Technologies, 1960-2002*, NHTSA Technical Report. DOT HS 809 833, pp. 25-31. Washington, DC: National Highway Traffic Safety Administration.
[4] Dang (2007).

1.2 Stopping-test findings

NHTSA carried out two extensive series of stopping tests at its East Liberty, Ohio, facility between 1988 and 1991. The agency tested 14 vehicles with four-wheel ABS (12 cars and 2 LTVs) and 3 pickup trucks with rear-wheel ABS.[5] The tests included a variety of road surfaces, straight-line stops at various speeds, and maneuvers requiring steering plus braking. Each vehicle was tested with the ABS enabled and disabled and with the vehicle empty and fully loaded. The road surfaces included dry concrete, three types of wet asphalt or concrete (different levels of smoothness), two slippery surfaces (wet Jennite and wet epoxy), and gravel. Wet Jennite (roadway sealant) has a much lower sliding than rolling coefficient of friction, making it likely to show an exceptional improvement in stopping distance with ABS. Wet epoxy has coefficients of friction similar to ice, although it is not intended as a surrogate for ice: unlike wet Jennite, the sliding coefficient of friction is only slightly lower than the peak-friction coefficient. The objectives of the tests were to study the effect of ABS on general directional stability, vehicle response to steering input, and stopping distances.

Table 1-1 shows that four-wheel ABS maintained excellent directional stability during straight-line stops on homogeneous surfaces.

TABLE 1-1: EFFECT OF **FOUR-WHEEL** ABS ON VEHICLE YAWING IN STRAIGHT-LINE SPIKE STOPS, BY TYPE OF ROAD SURFACE

		Number of Tests, by Angle of Yaw			
Road Surface	**ABS Status**	**No Yaw**	**$\leq 10^o$**	**$10\text{-}45^o$**	**$> 45^o$**
Dry concrete	Enabled	46			
	Disabled	40	6		
Wet asphalt/concrete	Enabled	276			
	Disabled	170	99	7	
Wet Jennite	Enabled	88			
	Disabled	16	37	24	11
Wet epoxy	Enabled	42			
	Disabled	10	22	5	5
Gravel	Enabled	42			
	Disabled	17	21	3	

[5] Hiltner, E., Arehart, C., & Radlinski, R. (1991). *Light Vehicle ABS Performance Evaluation*. NHTSA Technical Report. DOT HS 807 813. Washington, DC: National Highway Traffic Safety Administration; Arehart, C., Radlinski, R., & Hiltner, E. (1991). *Light Vehicle ABS Performance Evaluation – Phase II*, NHTSA Technical Report. DOT HS 807 924. Washington, DC: National Highway Traffic Safety Administration; Kahane, C. J. (1993). *Preliminary Evaluation of the Effectiveness of Rear-Wheel Antilock Brake Systems for Light Trucks*, pp. 9-14. NHTSA Docket No. 70-27-GR-026. Washington, DC: National Highway Traffic Safety Administration.

In a total of 494 tests, on different road surfaces, with ABS enabled, there was not a single case of yawing. With ABS disabled, some of the vehicles yawed on every surface. There was more yawing on the slippery surfaces. On dry concrete, only 6 of 46 tests with ABS disabled involved yawing, and always less than 10 degrees. On wet Jennite, 72 of 88 tests resulted in yawing, 11 of them more than 45 degrees.

Table 1-2 shows that rear-wheel ABS substantially, but not completely, reduced the yaw of pickup trucks. Even with the rear wheels rolling, front-wheel lockup can lead to moderate amounts of yaw. With the ABS enabled, the amount of yaw was always less than 10 degrees on wet asphalt/concrete and less than 45 degrees on wet Jennite, while there was yawing in excess of 45 degrees on both surfaces with the ABS disabled. On dry concrete and gravel, however, the tests did not show an advantage for rear-wheel ABS.

TABLE 1-2: EFFECT OF **REAR-WHEEL** ABS ON VEHICLE YAWING
IN STRAIGHT-LINE SPIKE STOPS, BY TYPE OF ROAD SURFACE

		Number of Tests, by Angle of Yaw			
Road Surface	**ABS Status**	**No Yaw**	**$\leq 10^o$**	**$10\text{-}45^o$**	**$> 45^o$**
Dry concrete	Enabled	12			
	Disabled	12			
Wet asphalt/concrete	Enabled	57	15		
	Disabled	39	26	2	5
Wet Jennite	Enabled	1	17	6	
	Disabled	0	11	10	3
Wet epoxy	Enabled	1	5		
	Disabled	0	6		
Gravel	Enabled	5	7		
	Disabled	6	6		

NHTSA also tested stops on heterogeneous surfaces that were more slippery under one side of the vehicle than the other (so-called "split-mu" surfaces) – e.g., wet epoxy under the left wheels and wet concrete under the right wheels. They resemble a roadway with slippery patches. Four-wheel and rear-wheel ABS were both highly effective in preventing or minimizing yaw in panic stops, whereas the yaw was often 180 degrees or more when the systems were disabled.

For a test of combined braking and steering, the vehicles with four-wheel ABS were subjected to emergency stops in a curve or lane-change maneuver on wet asphalt or Jennite. In all cases, the vehicles successfully negotiated the maneuvers during panic braking with the ABS enabled.

Vehicles with rear-wheel ABS experienced front-wheel lockup during panic braking and could not be steered around the curve or to another lane.

The effect on stopping distance in straight-line panic stops is not uniformly beneficial for four-wheel ABS and, in fact, somewhat negative for rear-wheel ABS. Table 1-3 shows the median percentage reduction of stopping distance, by road surface type, for a test with ABS enabled relative to the corresponding test with ABS disabled. Four-wheel ABS reduced stopping distances by only 5 percent on dry concrete, but had a substantially larger effect on wet asphalt or concrete (14 percent on the average). Because wet Jennite has a much higher rolling resistance than sliding resistance, the reduction in stopping distance for ABS is 43 percent. Jennite is not extensively used to pave real highways, but there are certain conditions where actual pavements can approach the characteristics of Jennite (wet, highly worn, dirty and/or oily). The much smaller reduction on wet epoxy (10%) suggests that the exceptional result on Jennite is due to the characteristics of that material and is not true for all slippery materials (e.g., ice). Finally, four-wheel ABS lengthens stopping distances on gravel by 28 percent: A car with the wheels locked causes gravel to build up in front of the wheels, resulting in a plowing effect that slows the vehicle quicker than ABS (although steering control is lost and the car may yaw). Surfaces with other loose material, such as snow, would have a similar effect.

TABLE 1-3: EFFECT OF ABS ON STOPPING DISTANCE
IN STRAIGHT-LINE SPIKE STOPS, BY TYPE OF ROAD SURFACE

	Median Percent Reduction of Stopping Distance ABS Enabled Versus ABS Disabled	
Road Surface	Four-Wheel ABS	Rear-Wheel ABS
Dry concrete	5	– 6
Wet asphalt/concrete	14	– 6
Wet Jennite	43	7
Wet epoxy	10	– 12
Gravel	– 28	– 18

Rear-wheel ABS lengthens stopping distances on all surfaces except wet Jennite; the increase is 6 percent on dry or wet concrete/asphalt. In general, a truck with four wheels sliding stops a little sooner than a truck with the front wheels sliding and the rear wheels rolling. However, keeping the rear wheels rolling greatly improves directional stability.

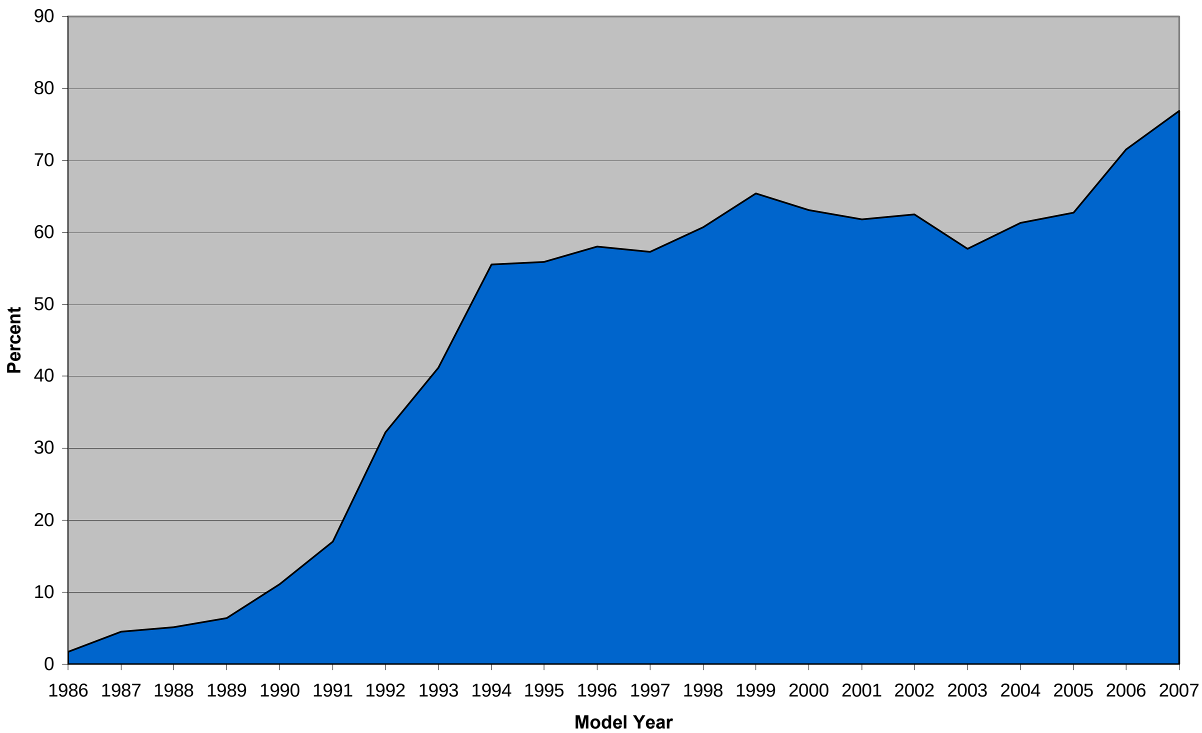
In summary, NHTSA's tests show that four-wheel ABS is effective, especially on wet pavements, in improving overall vehicle stability during braking, preserving the ability to steer, and reducing stopping distances. Rear-wheel ABS, on the other hand, did not reduce stopping distance or preserve steering control during braking; benefits were limited to improved directional stability.

Nevertheless, the test results do not take into account phenomena that may limit the utility of ABS in actual crashes. The tests were performed by expert drivers who knew they had to apply firm pressure on the brakes in combination with relatively delicate evasive steering. The average driver in a panic situation might have difficulty combining firm braking with delicate steering, and might be too timid with the pedal or too bold with the steering wheel. The stopping tests also did not include maneuvers where vehicles were sliding even before the brakes were applied.

1.3 Market and regulatory history

Modern four-wheel ABS was first offered as standard equipment in 1985 on some lines of BMW, Lincoln and Mercedes and in 1986 on Chevrolet Corvette. Consumers liked the technology. Availability of ABS increased gradually from 1987 to 1990 and dramatically in 1991 and 1992, when it became standard on the majority of GM cars. By the mid-1990s, ABS was standard or a popular option on a wide variety of cars comprising the principal manufacturers. Figure 1-1 shows that from 1994 onwards at least 55 percent of new passenger cars have been equipped with ABS each model year.[6]

FIGURE 1-1: PERCENT OF CARS WITH ABS, BY MODEL YEAR



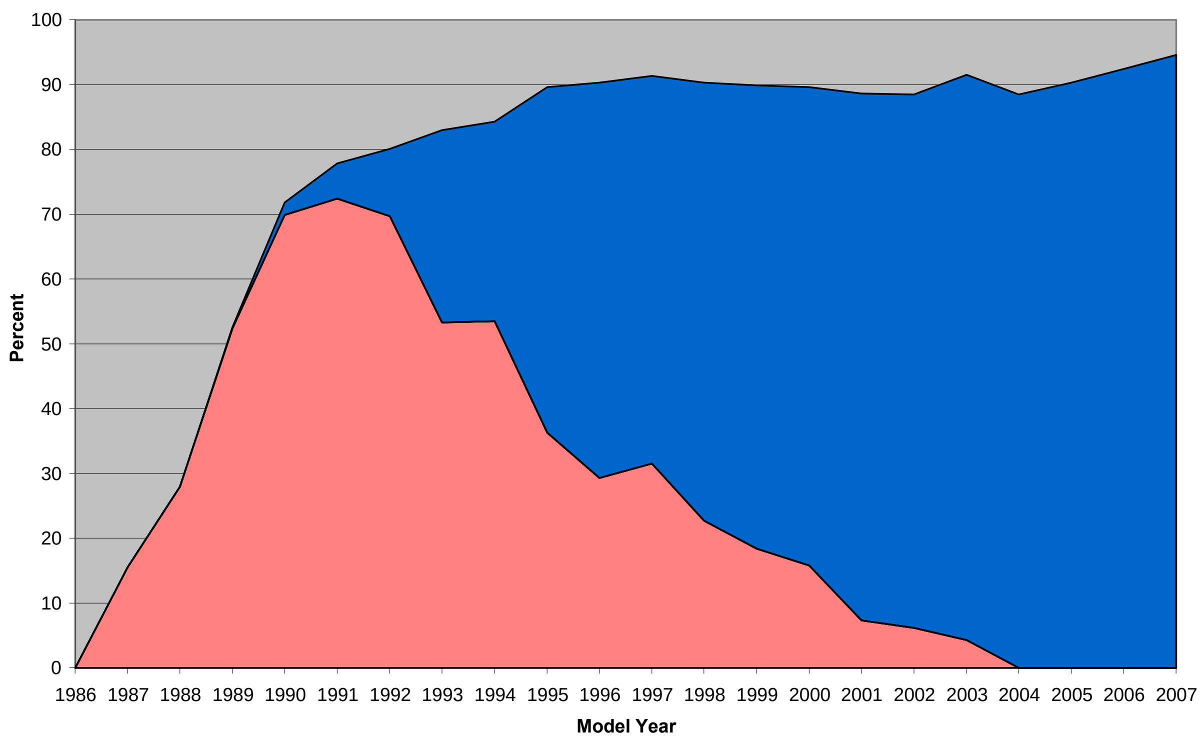
In general, ABS has usually been standard on the larger and the more expensive cars, optional and not too frequently sold on small economy cars, and standard or a popular option on the mid-size cars with high sales. Market share dropped from 1999 to 2003 as several makes and models

[6] *Ward's Automotive Yearbooks, 1987-2008*. Detroit: Ward's Communications; tables of factory-installed equipment on vehicles of the preceding model year.

dropped standard ABS and made it optional, but rebounded after 2005 as other models with high sales made ABS standard after their latest redesign.

Rear-wheel ABS first appeared as standard equipment in 1987 Ford F-Series pickup trucks, Bronco, and Bronco II. By 1988 to 1990, it was standard in most domestic pickup trucks and SUVs as well as many vans. Four-wheel ABS installations for LTVs began in 1989 on some Chevrolet Astro and GMC Safari minivans, Jeep Cherokee, and Jeep Wagoneer. Figure 1-2 shows that from 1995 onwards, 90 percent of new LTVs were equipped with either rear-wheel (pink region) or four-wheel (blue region) ABS. However, during model years 1992 to 2002, four-wheel systems rapidly superseded rear-wheel ABS. By 2004, only four-wheel ABS was available on new vehicles.

FIGURE 1-2: PERCENT OF LTVs WITH REAR-WHEEL AND FOUR-WHEEL ABS, BY MODEL YEAR



ABS has not to date been explicitly required for passenger vehicles with GVWR less than 10,000 pounds. But there was some movement in that direction in the early 1990s, obviously spurred by the outstanding performance of ABS on the test track. The Intermodal Surface Transportation Efficiency Act of 1991, Section 2507 instructed NHTSA to initiate rulemaking, by December 31, 1993, to consider the need for additional brake-performance standards for light vehicles, including ABS.[7] The agency published an Advance Notice of Proposed Rulemaking on January 4, 1994, asking for information about the effectiveness and potential benefits of ABS technologies.[8]

[7] Public Law 102-240, December 18, 1991.
[8] *Federal Register* 59 (January 4, 1994): 281.

By 1994, production vehicles with rear-wheel and four-wheel ABS had accumulated enough on-the-road experience for preliminary statistical evaluations to see if the effect of ABS on actual crashes matched the promise it showed on the test track. These studies, which will be discussed in the next section, failed to show significant net benefits for ABS. Based on these analyses, as well as other responses to the 1994 ANPRM, NHTSA issued a second ANPRM on July 12, 1996, deferring indefinitely any ABS requirement for light vehicles.[9]

1.4 Initial effectiveness analyses

Because rear-wheel ABS for LTVs began to appear in large numbers several years before four-wheel ABS for cars or LTVs, the first statistical analysis was NHTSA's December 1993 evaluation of rear-wheel ABS.[10] The basic approach in this study, as well as most of the others, is to compare the ratio of response-group to control-group crashes in vehicles with ABS to the corresponding ratio in vehicles without ABS. The response groups comprise types of crash involvements that ABS might prevent if it improves directional stability, steering control, or stopping distance (or increase if it worsens any of these): run-off-road crashes, involvements as the frontally impacting vehicle in collisions with other vehicles, and collisions with pedestrians. The control group consists of crash involvements that are unaffected by ABS, such as being hit while standing still.

Because rear-wheel ABS has little effect on steering control and perhaps even a negative effect on stopping distance, the most likely expected benefit would be a reduction in run-off-road crashes, such as rollovers and collisions with fixed objects. Indeed, analyses of crash data from Florida, Michigan, and Pennsylvania showed statistically significant reductions of <u>nonfatal</u> rollovers averaging 30 percent and side impacts with fixed objects averaging 20 percent.[11] There was little or no effect on nonfatal involvements in collisions with other vehicles.[12]

However, corresponding analyses of FARS data did not show reductions of <u>fatal</u> run-off-road crashes.[13] FARS analyses of fatal involvements in multi-vehicle collisions showed a mix of zero and negative effectiveness.[14] Pedestrian crashes were the only type with a significant fatality reduction, on the order of 10 percent, but it was not clear why rear-wheel ABS should be effective there.[15]

NHTSA issued a second FARS analysis of rear-wheel ABS in 1995, based on logistic regressions rather than contingency table analyses, the method of the previous study.[16] This report associated rear-wheel ABS with a statistically significant increase of fatal involvements as the striking vehicle in a multi-vehicle collision. It did not find a reduction of fatal run-off-road

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[9] *Federal Register* 61 (July 12, 1996): 36698.
[10] Kahane (1993).
[11] *Ibid*., pp. 19-44 and 108.
[12] *Ibid*., pp. 100-109.
[13] *Ibid*., pp. 42-49 and 100-109.
[14] *Ibid*., pp. 78-85.
[15] *Ibid*., pp. 93-99 and 108.
[16] Hertz, E., Hilton, J., & Johnson, D. M. (1995a). *An Analysis of the Crash Experience of Light Trucks Equipped with Antilock Braking Systems*. NHTSA Technical Report. DOT HS 808 278. Washington, DC: National Highway Traffic Safety Administration.

crashes. Pedestrian crashes were not considered in that study. By 1995, four-wheel ABS was rapidly superseding rear-wheel ABS in LTVs, and the effectiveness of the rear-wheel systems became a moot point.

The first statistical analysis of four-wheel ABS for passenger cars was published by the Highway Loss Data Institute in January 1994.[17] It is based on the frequency and cost of collision damage claims per 1000 insured vehicle years in MY 1992 models with standard ABS versus the same models in MY 1991 without ABS. HLDI found that ABS had little or no effect. However, the data mix all types of crashes and contain a large percentage of low-speed collisions that are unlikely to be affected by ABS. The results did not preclude the possibilities that ABS might have an effect in crashes of higher severity or might be beneficial in certain crash types and harmful in others.

A May 1994 study of the effects of ABS in Sweden was the first publication indicating that ABS was associated with a statistically significant shift from colliding with other vehicles to running off the road. The paper did not fully resolve whether this happened because ABS reduced collisions with other vehicles, increased run-off-road crashes, or both. But it first revealed a pattern that would reappear in almost every subsequent analysis. Furthermore, it showed this pattern in a different country, with a substantially different mix of makes and models on the road.[18]

NHTSA's preliminary evaluation of four-wheel ABS for passenger cars is dated December 1994.[19] The analysis is based on FARS data from 1989 to 1993. In multi-vehicle crashes on dry roads, the ratio of involvements as a frontally impacting car to involvements as a car that was struck in the rear or side, or while standing still, was nearly the same with or without ABS. That suggests ABS has, at most, a small effect on multi-vehicle crashes on dry roads. For the remaining analyses, multi-vehicle crash involvements on dry roads (regardless of impact type) serve as the control group.[20] Multi-vehicle crash involvements on wet roads were reduced by a statistically significant 24 percent with ABS:[21]

FARS 1989-93 MULTI-VEHICLE CRASHES	Wet Roads	Dry Roads	Ratio of Wet/Dry
Last 2 model years without ABS	246	1,021	.241
First 2 model years with ABS	158	858	.184

Fatal collisions with pedestrians, bicyclists, trains, or animals, on all road surfaces, were reduced by a statistically significant 27 percent.[22]

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[17] *Collision and Property Damage Liability Losses of Passenger Cars With and Without Antilock Brakes*. (1994). Insurance Special Report No. A-41., Arlington, VA: Highway Loss Data Institute.
[18] Kullgren, A., Lie, A., & Tingvall, C. (1994). The Effectiveness of ABS in Real Life Accidents, *Proceedings of the Fourteenth International Technical Conference on the Enhanced Safety of Vehicles*, Paper No. 94-S4-O-07. Washington, DC: National Highway Traffic Safety Administration.
[19] Kahane (1994).
[20] *Ibid*., pp. 57-62.
[21] *Ibid*., p. 65.
[22] *Ibid*., pp. 63-68.

But fatal run-off-road crashes (rollovers and impacts with fixed objects) increased by a statistically significant 28 percent on all road surfaces, with ABS:[23]

FARS 1989-93	Rollover + Fixed Object	Dry-Road Multi-Vehicle	Ratio
Last 2 model years without ABS	431	1,021	.422
First 2 model years with ABS	463	858	.540

The increases were about equally large on dry, wet, and snowy/icy roads. In particular, side impacts with fixed objects, a crash type typically preceded by loss of directional control, increased by a statistically significant 57 percent. The increase in run-off-road crashes nearly offset the reductions in pedestrian and wet-road multi-vehicle crashes, resulting in a near-zero net effect on overall fatal-crash risk.[24]

The report's analysis of nonfatal crashes is based on Florida, Missouri, and Pennsylvania data from 1990 to 1992.[25] Here, the control group consisted of cars struck while standing still or moving 5 mph or less. On wet roads, cars with ABS experienced a statistically significant, 28 percent reduction of frontal impacts, relative to the control group and relative to cars of the same makes and models without ABS.[26] For all road conditions (wet, dry, snowy, icy), the overall reduction in multi-vehicle frontal impacts with ABS was a statistically significant 9 percent. Nonfatal run-off-road crashes, however, increased rather than decreased with ABS. Relative to the control group, rollovers and fixed-object impacts increased overall by a statistically significant 19 percent in the ABS-equipped cars.[27]

In May 1995, NHTSA published a second statistical analysis of ABS in passenger cars, based on data from 1989 to 1993 from FARS and four States, using logistic regression rather than contingency-table analyses. It confirmed the statistically significant increases of rollovers and side impacts with fixed objects in the ABS-equipped cars, in both fatal and nonfatal crashes. It also confirmed the benefits of ABS in fatal and nonfatal multi-vehicle crashes on wet roads.[28] Furthermore, NHTSA's initial analysis of four-wheel ABS in LTVs showed similar increases (although not statistically significant) of rollovers and side impacts with fixed objects in the LTVs with the four-wheel ABS.[29]

In 1996, the Insurance Institute for Highway Safety issued a study examining fatal crash involvements from CY 1993 to 1995 of selected vehicles for the model year prior to the

[23] *Ibid*., p. 95.
[24] *Ibid*., pp. 115-117.
[25] *Ibid*., pp. 10-57.
[26] *Ibid*., p. 53.
[27] *Ibid*., p. 84-92.
[28] Hertz, E., Hilton, J., & Johnson, D. M. (1995b). *An Analysis of the Crash Experience of Passenger Cars Equipped with Antilock Braking Systems*. NHTSA Technical Report. DOT HS 808 279. Washington, DC: National Highway Traffic Safety Administration.
[29] Hertz (1995a).

introduction of ABS and the model year after ABS became standard equipment.[30] IIHS observed a 28-percent increase in run-off-road crashes with ABS, identical to the increase observed by NHTSA. IIHS also found that vehicles equipped with ABS were more likely to be involved in crashes fatal to their own occupants (particularly single-vehicle crash involvements) but less likely to be involved in crashes fatal to occupants of non-ABS equipped vehicles or non-occupants (pedestrians, bicyclists). Overall, ABS had little effect on fatal crash involvements.

1.5 The safety community's response

The various initial effectiveness analyses seemed to agree that:

- The overall effect of ABS on fatal crash involvements was close to zero.
- Vehicles with four-wheel ABS had significantly higher rates of fatal run-off-road crashes than vehicles without ABS. In fact, the overall effect netted out to zero only because this increase was offset by a reduction in collisions with other vehicles on wet roads.

These fairly strong statistical results did not square with intuition. The behavior of ABS on the test track did not provide any obvious reason that run-off-road crashes should increase; if anything, they suggested there ought to be a benefit.

With the coordination of NHTSA's Motor Vehicle Safety Research Advisory Committee, government, industry, and the safety community discussed possible reasons for the observed increases in run-off-road crashes. These were the principal hypotheses:

- Driver inexperience/lack of knowledge about ABS. Drivers might remove their foot from the pedal in response to the [unanticipated] noise and vibration of ABS, or try to pump the pedal as with conventional brakes.
- A misperception of how much ABS reduces stopping distances or enhances control. Some drivers may negotiate curves or change lanes more aggressively because they believe ABS will enable them to stop in a shorter distance or retain control of their vehicle in extreme driving maneuvers.
- Longer stopping distances with ABS on the loose surfaces that vehicles encounter after they leave the road.
- The enhanced steering control while braking with ABS could allow unsafe panic steering maneuvers. An inexpert driver in a panic situation might try an abrupt evasive steering maneuver while slamming on the brakes. Without ABS, the front wheels lock; the car goes straight ahead, essentially ignoring the steering input. With ABS, the vehicle responds to the abrupt, instinctive steering input, possibly running off the road and badly out of control.
- Possible flaws in the performance of the early ABS technologies in certain maneuvers or on some roadway surfaces.

[30] Farmer, C. M., Lund, A. K., Trempel, R. E., & Braver, E. R. (1996). *Fatal Crashes of Passenger Vehicles Before and After Adding Antilock Brake Systems*. Arlington, VA: Insurance Institute for Highway Safety.

- The increase in run-off-road crashes was not due to ABS. It was due to concurrent changes in some makes and models that were equipped with ABS, such as increased horsepower or a sportier image.

NHTSA undertook a multiyear research program to test out these and other hypotheses.[31] The activities included:

- In-depth reviews of cases involving ABS-equipped cars that ran off the road.
- Interviews with drivers who complained to the NHTSA's Auto Safety Hotline about the performance of their ABS systems.
- Discussions with crash investigators and police officers who drive ABS-equipped vehicles or who investigate crashes involving ABS-equipped vehicles.
- A study, conducted on the driving simulator, of how average drivers respond to imminent crash threats.
- A "naturalistic" study that tracked the maneuvers of average drivers over extended time periods.
- Combined braking-and-steering tests to establish the range of maneuvers that can be successfully executed without a loss of directional control.

The research, in fact, did not identify any significant problems with ABS other than owners' initial lack of knowledge and experience with the systems. There was little evidence of any behaviors that would cause drivers of vehicles equipped with ABS to run off the road. There was also little evidence that drivers became more aggressive when they had ABS.

Beginning in 1995, NHTSA, the manufacturers, ABS suppliers (who had formed an ABS Education Alliance[32]), and the insurance industry developed media to educate vehicle owners about how ABS responds when activated, and how to use it properly. Some of the main points were:

- Do not pump the brake pedal in cars equipped with ABS. This can defeat the purpose of ABS and may reduce braking capability. Don't let up on the brakes. Stomp, stay, and steer.
- The ABS system can make noise and vibrate the brake pedal when it is working. Drivers should not take their foot off the brake pedal when they hear noise or feel pedal vibration.
- Drivers should be aware that extreme steering maneuvers executed while using ABS brakes could steer the car off the road.
- ABS can significantly lengthen stopping distances on loose surfaces such as gravel or soft snow. Drivers should slow down and allow extra distance between vehicles under those conditions.

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[31] Kahane (1994), pp. v-viii.
[32] http://www.abs-education.org.

- Many drivers think the main purpose of ABS is to reduce stopping distances. This is a serious misconception. ABS will only reduce stopping distances significantly in some special road conditions, but may increase distances in others.
- The principal goals of ABS are to prevent skidding and loss-of-control due to locked-wheel braking and to allow a driver to steer the vehicle during hard braking.
- If a driver makes a car skid for reasons other than braking, such as going around a curve too quickly, ABS will not prevent or relieve the skid.
- Drivers of cars equipped with ABS must maintain the same distance behind vehicles they follow that they would have kept without ABS. They should not expect to stop more quickly because they have ABS.
- Drivers of cars equipped with ABS should not drive around curves, change lanes, or perform other steering maneuvers any faster or more aggressively than they would have without ABS. They should not expect ABS to improve their control in these maneuvers.

1.6 The second generation of effectiveness analyses

By the late 1990s, NHTSA and the safety community were satisfied that consumers understood how to use ABS properly and had become familiar with ABS. None of the other hypotheses for the increase in run-off-road crashes was confirmed by empirical evidence. It was time to analyze new data and see if the effect was still there. Three reports published in 2000-02 suggest that the increase in run-off-road crashes may have been largely or entirely temporary.

NHTSA's follow-up analysis in 2000 used the same logistic regression models as its 1995 reports, but applied them to FARS and State data from calendar years 1995 and 1996 rather than 1989 to 1993.[33] Makes and models included those with standard ABS considered in the previous studies, supplemented by models that offered optional ABS. The observed effects of ABS in passenger-car rollovers and side impacts with fixed objects were still negative, but less than half as large as in the 1995 study. They were no longer statistically significant. The observed effect in frontal impacts with fixed objects had crossed from a non-significant negative to a non-significant positive. There were non-significant reductions in collisions with pedestrians and in frontal collisions with other vehicles. Four-wheel ABS did not have a statistically significant effect on any type of fatal crash, except for an increase in LTV rollovers. Several types of nonfatal crash involvements were significantly reduced with ABS: rollovers, frontal impacts with fixed objects, and frontal impacts into other vehicles. The report did not estimate the overall effect of ABS on fatal or on nonfatal crashes.

The IIHS follow-up study of 2001 compared the crash experience of models in the first model year after receiving four-wheel ABS as standard equipment to the experience of the same models in the last model year before ABS.[34] Whereas run-off-road crashes increased significantly with

[33] Hertz, E. (2000). *Analysis of the Crash Experience of Vehicles Equipped with All Wheel Antilock Braking Systems (ABS) – A Second Update Including Vehicles with Optional ABS*, NHTSA Technical Report. DOT HS 809 144. Washington, DC: National Highway Traffic Safety Administration..

[34] Farmer, C. M. (2001). New Evidence Concerning Fatal Crashes of Passenger Vehicles Before and After Adding Antilock Braking Systems, *Accident Analysis and Prevention*, Vol. 33, pp. 361-369.

ABS during CY 1993 to 1995 these same MY models no longer experienced a significant increase in run-off-road crashes during CY 1996 to 1998. However, this study did not find a statistically significant overall effect for ABS on fatal crashes in 1996-98; it did not analyze nonfatal crashes.

Harless and Hoffer confirmed the IIHS results and, moreover, presented evidence that the increase in run-off-road crashes during the CY 1993 to 1995 was virtually confined to drinking drivers.[35] It was especially prevalent in young, drinking drivers or in drinking drivers with a history of high-risk driving behavior. Fatal crash involvements of drinking drivers of ABS-equipped vehicles were 64 percent higher than expected during 1993 to 1995, given the number of fatal crash involvements of drinking drivers of non-ABS vehicles of the same makes and models. The number of involvements of non-drinking drivers of ABS-equipped vehicles was 11 percent lower than expected during those years. But in CY 1996 to 1998, there was no observed increase in crashes with ABS even for the drinking drivers. Harless and Hoffer suggested that drinking drivers were at first especially unaware and unable to use ABS properly, but eventually improved at least their knowledge of ABS, if not their driving skills.

These studies apparently satisfied the safety community that the initial increase in run-off-road crashes with ABS, if it was "real" at all, must have been largely due to owners' inexperience and lack of knowledge about the systems. Thanks to the efforts to educate the public about ABS, and as owners simply accumulated years of experience with their vehicles, the increase in run-off-road crashes ostensibly faded away. Subsequent improvements in ABS technology perhaps also helped, such as better response and feedback to the driver or the "brake assist" feature on some vehicles, which amplifies input from the driver.

The consensus appeared to be that no further regulatory action was needed:

- Because there was no significant overall fatality reduction, there was little motivation to reverse the July 12, 1996, decision to shelve any ABS requirement.
- Because the adverse effect on run-off-road crashes was becoming a thing of the past, there was no need to consider regulation addressing that issue.
- To the extent that ABS was technology that many customers desired because it enhanced vehicle performance – even if it had no quantifiable safety benefits, and if it did help reduce nonfatal crashes, all the better – it was satisfactory to just let market forces establish the demand for ABS.

However, a possible flaw in the logic is that the observed effects on run-off-road crashes were sill negative. They were just no longer statistically significant – in part, because they were based on relatively small numbers of cases. One study was based on two calendar years of data (1995 to 1996); the others were based on three years (1996 to 1998), but they limited the data to the last model year before ABS and the first model year with ABS. While the observed effects were not as negative as in the earlier studies, there was still a fair amount of uncertainty about them.

[35] Harless, D. W., & Hoffer, G. E. (2002). The Antilock Braking System Anomaly: A Drinking Driver Problem? *Accident Analysis and Prevention*, Vol. 34, pp. 333-341.

Another flaw is that none of the analyses adjusted for the effect of frontal air bags. It so happened that many models of cars and LTVs were equipped with frontal air bags in the same model year or within a year of when they received four-wheel ABS. Air bags save lives in frontal impacts, including frontal run-off-road crashes. Unless the FARS analyses adjust in some way for the effect of air bags, they spuriously attribute a reduction of frontal fatal crash involvements to ABS, when that reduction is in fact due to the air bags changing the crashes from fatal to nonfatal.

The logic could also be flawed under the "best case" assumption: that the negative effect on fatal run-off-road crashes had really ended. If so, wouldn't the positive effects in other types of fatal and nonfatal crashes still be there, resulting in a potentially significant net benefit for ABS?

1.7 Developments since 2002

Electronic stability control is surely the most exciting development in crash-avoidance technology during the past decade. ESC monitors the speed of each wheel, the steering wheel angle, the overall yaw rate, and the lateral acceleration of the vehicle. It compares a driver's intended course with the vehicle's actual movement and detects when a driver is about to lose control. It intervenes in split seconds by automatically applying the brakes to any one or to several individual wheels – or by reducing engine torque – to provide stability and help the driver stay on course. It may then slow down the vehicle to a speed more appropriate for conditions. ESC can prevent an impending crash even before a driver is aware of the danger. It can activate even if a driver does nothing, unlike ABS, which cannot activate until a driver has applied the brakes.

Mercedes-Benz first offered ESC on selected cars in 1997; Cadillac and BMW in 1998. By 2000 it was standard on a fair number of luxury cars. Among SUVs, ESC was standard on Mercedes in 1999 and on selected Toyota and Lexus models in 2000 or 2001. By 2004, vehicles had accumulated enough on-the-road experience for preliminary statistical analyses of crash data, indicating large reductions of fatal rollovers and other single-vehicle crashes.[36] The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users of 2005 (SAFETEA-LU), Section 10301 asked NHTSA to publish, by October 1, 2006, a Notice of Proposed Rulemaking on stability-enhancing technologies and a final rule by April 1, 2009.[37] The agency published a NPRM on September 18, 2006, and a final rule on April 6, 2007, establishing FMVSS No. 126, which will require ESC on all new cars and LTVs by September 1, 2011, with a phase-in period beginning September 1, 2008.[38] NHTSA's latest statistical analysis (2007) found that ESC significantly reduces fatal run-off-road crashes by an estimated 36 percent in passenger cars and by 70 percent in LTVs, relative to vehicles of the same makes and models equipped with four-wheel ABS but not ESC.[39] In MY 2007, two model years before

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[36] Dang, J. N. (2004). *Preliminary Results Analyzing the Effectiveness of Electronic Stability Control (ESC) Systems.,* NHTSA Evaluation Note. DOT HS 809 790. Washington, DC: National Highway Traffic Safety Administration..
[37] Public Law 109-59, August 10, 2005.
[38] *Federal Register* 71. September 18, 2006: 54712; 72, April 6, 2007: 17310.
[39] Dang (2007), p. vii.

the beginning of the phase-in period, 22 percent of the new cars and 53 percent of the new LTVs sold in the United States were already equipped with ESC.[40]

All ESC-equipped vehicles to date are also equipped with four-wheel ABS. It is not merely a marketing issue (ESC initially being offered on the more expensive models that have long been ABS-equipped), but an intrinsic tie between the technologies. The functional capabilities inherent to ABS – namely, monitoring the speed of each wheel and automatically modulating the brake at individual wheels – are a subset of the functional capabilities of ESC. To date, ESC hardware has included within it the components needed to perform ABS functions. For the foreseeable future, FMVSS No. 126 will be a regulation that *de facto* puts ABS into all new cars and LTVs.

1.8 Goals of the evaluation

It is time for a new evaluation of ABS, as discussed in NHTSA's 2008-2012 evaluation plan.[41] The agency evaluates the effectiveness of its existing regulations, as required by The Government Performance and Results Act of 1993[42] and Executive Order 12866[43] and it also evaluates the effectiveness of major safety technologies that are available in production vehicles, even if not required by a regulation. ABS is certainly a major technology, and it will soon be in all new vehicles, even if it is not explicitly mandated by a regulation. Moreover, NHTSA may re-evaluate a technology if its effectiveness is suspected of changing over time, and will do so until the long-term effect is identified.[44]

As of April 2009, crash data are available through CY 2007. Databases are now many times larger than the ones available for the first- and second-generation effectiveness studies. Main estimates will be statistically significant unless they are within a few percentage points of zero. The databases will not get much larger in the future, because the vehicles of the early 1990s that play a critical role in the analyses have been retired or are approaching the end of their service lives.

The principal evaluation questions are:

- What is the long-term overall effect of ABS on fatal crashes?
- What is the long-term effect of four-wheel ABS on fatal run-off-road crashes?
    - If it is negative, how does it compare to the effect of ESC? FMVSS No. 126 will require all vehicles to be equipped with ESC, and it is almost certain they will

[40] *Ward's Automotive Yearbook 2008*.
[41] Allen, K., Dang, J. N., Doyle, C. T., Kahane, C. J., Roth, J. R., & Walz, M. C. (2008). *Evaluation Program Plan, 2008-2012* pp. i and 9. NHTSA Technical Report. DOT HS 810 983. Washington, DC: National Highway Traffic Safety Administration.
[42] Public Law 103-62, August 3, 1993.
[43] *Federal Register* 58, October 4, 1993.
[44] Kahane, C.J., & Hertz, E. (1998). *The Long-Term Effectiveness of Center High Mounted Stop Lamps in Passenger Cars and Light Trucks*. NHTSA Technical Report. DOT HS 808 696. Washington, DC: National Highway Traffic Safety Administration.

also be equipped with ABS. How does the risk of fatal run-off-road crashes of vehicles with ESC and ABS compare to the risk in vehicles with neither?

  - If the effect of ABS on fatal run-off-road crashes is close to zero, does ABS now have enough positive effects in other types of crashes to result in a significant overall fatality reduction?

- What is the overall effect of ABS on nonfatal crashes? Even if the net effect of ABS on fatal crashes is close to zero, does ABS prevent enough nonfatal injuries and property damage to endorse ABS technology for its safety benefits?

CHAPTER 2

EFFECT OF ABS IN FATAL CRASHES: ANALYSES OF 1995-2007 FARS DATA

2.0 Summary

ABS has close to a zero net effect on fatal crash involvements. The observed net effects are a 1-percent reduction of fatal crashes for passenger cars and a 1-percent increase for LTVs. Neither is statistically significant. But ABS is not without effect. Run-off-road crashes significantly increase while collisions with pedestrians are significantly reduced, as are collisions with other vehicles on wet roads. However, the mix of these collision types among fatal crashes is such that the added harm and the benefits cancel each other.

2.1 Analysis for passenger cars

2.1.1 FARS calendar-year range

FARS is a census of fatal crashes in the United States since 1975. As of April 2009, the FARS database is complete through calendar year 2007. Because the goal is to study the "long-term" effect of ABS and not its "initial" effects, only calendar years 1995-2007 are included in the analysis. CY 1995 has been selected as the starting point for the data because it was also the starting point in Hertz's 2000 report, the first to indicate that the initially deleterious effect of ABS on run-off-road crashes had become non-significant.[45] Furthermore, statistical analyses[46] indicating relative increases in run-off-road crashes with ABS had appeared in 1994 and by 1995 the industry was responding with consumer information on the correct use of ABS.

The basic analysis approach is to count the number of fatal crash involvements of various types that might conceivably be influenced by ABS and compute their ratios to the number of control group involvements that are unlikely to be affected by ABS. The ratios are compared for cars with ABS and cars of the same makes and models without ABS – in the same calendar years.

2.1.2 Control-group involvements versus response group

The control group and the response group are similar to the ones in NHTSA's evaluation of electronic stability control.[47] An ideal control group would be cars that had been stopped or parked before they were hit by another vehicle. Obviously, ABS in those cars could not have made a difference if they were standing still even before the sequence of events that resulted in a collision. But there are too few fatal crashes involving stationary cars to obtain statistically meaningful results from analyses employing this control group. It is necessary to supplement the control group with other crash types where the possible influence of ABS is quite small, even if

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[45] Hertz, E. (2000). *Analysis of the Crash Experience of Vehicles Equipped with All Wheel Antilock Braking Systems (ABS) – A Second Update Including Vehicles with Optional ABS*. NHTSA Technical Report. DOT HS 809 144. Washington, DC: National Highway Traffic Safety Administration.

[46] Kullgren, A., Lie, A., & Tingvall, C. (1994). The Effectiveness of ABS in Real Life Accidents, *Proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles*, pp. 1568-73. Washington, DC: National Highway Traffic Safety Administration,; Kahane (1994).

[47] Dang (2007).

it cannot be completely ruled out. Involvements of cars that were moving less than 10 mph, backing up, parking, or leaving a parking space may be included, because ABS is unlikely to affect braking performance substantially at those low speeds. Cars struck in the rear while moving on any surface and cars involved as non-culpable parties in collisions with other vehicles on dry surfaces are also included. FARS does not provide detailed information on the braking performance of these cars. But in all likelihood these are not cars that hit somebody else because they went out of control during braking or could not stop in time (two things that ABS might prevent, depending on the surface), for in most cases they were simply proceeding as intended and did nothing to precipitate a collision.

The FARS codes for control group crashes include the following involvements in collisions with other vehicles (VE_FORMS ≥ 2):

- Hit while stopped/parked: VEH_MAN = 4, 7 or TRAV_SP = 0
- Backing/parking/low-speed: VEH_MAN = 3, 6, 8, 15 or TRAV_SP = 1-10
- Struck in rear: IMPACT1 = 5, 6, 7
- Non-culpable involvements on dry roads: SUR_COND = 1; none of the "driver contributing factors" DR_CF1, DR_CF2, DR_CF3, or DR_CF4 has a value that suggests this driver was culpable, namely codes 3, 6, 8, 26, 27, 28, 30, 31, 33, 35, 36, 38, 39, 44, 46, 47, 48, 50, 51, 57, 58, 79, or 87

All crash involvements that are not in the control group are in the response group. On roads that are not dry, even non-culpable involvements can be in the response group, because ABS is likely to benefit drivers in many situations and we do not want to "miss" a possible benefit just because FARS classified a driver as non-culpable. In other words, on roads that are not dry, the control group is limited to the first three of the four categories listed above. Effectiveness of ABS (percent crash reduction relative to the control group) is computed for the response group as a whole, and also for the following subgroups – on all roads, and on roads that are not dry:

- Run-off-road crashes: VE_FORMS = 1, but excluding HARM_EV = 2, 5, 8, 9, 10, 11, 14, 16, or 49 (collisions with non-motorists, trains, or parked cars, plus various non-collisions that usually happen on, not off the road)
  - First-event rollovers: ROLLOVER = 1 or HARM_EV = 1
  - Side impacts with fixed objects: IMPACT1 = 2, 3, 4, 8, 9, or 10
  - All other run-off-road crashes
- Collisions with pedestrians, bicyclists, other non-motorists, or animals: VE_FORMS = 1 and HARM_EV = 8, 9, 11 or 49
- Culpable involvements in collisions with other vehicles, including <u>any</u> frontal impact into the rear of another vehicle: at least one of the "driver contributing factors" DR_CF1, DR_CF2, DR_CF3, or DR_CF4 has a value that suggests this driver was culpable, namely codes 3, 6, 8, 26, 27, 28, 30, 31, 33, 35, 36, 38, 39, 44, 46, 47, 48, 50, 51, 57, 58, 79, or 87; <u>or</u> MAN_COLL = 1 and IMPACT1 = 1, 11, or 12

2.1.3 Cars without ABS versus cars with ABS

ABS can be standard equipment on a make and model in a given model year, or an option, or not available at all – or it may be standard on some sub-series of that model, optional on others, and unavailable on yet others. For the "cleanest" analysis, the models included should ideally change from not offering ABS at all in one model year to having it as standard equipment the next year. However, not that many models received ABS that way. Many of those that did were General Motors cars, not a representative cross-section of the entire fleet. Therefore, makes and models will also be included even if they switched from something more than 0 percent ABS and/or to something less than 100 percent ABS, as long as the percentage-point gain in ABS is substantial. The analyses will include an adjustment factor to translate the observed effect to the effectiveness of changing from 0 to 100 percent ABS.

Ward's Automotive Yearbooks began in MY 1986 to specify the percentage of cars of a make, model, and model year equipped with ABS. The few installations before 1986 are listed in NHTSA's 1994 evaluation report (based on information furnished by the manufacturers or from news articles).[48]

The cars without ABS should be as similar as possible to the cars with ABS, so as to avoid biases due to different types of driving or exposure. They should be the same makes and models. They should be of similar vehicle age. Their crash experience should be from the same calendar years. Those goals are accomplished by limiting the database to specific makes and models that shifted from a low ABS installation rate in one year to a high rate in the next year, or vice-versa – and further limiting the data to the last two model years before the shift versus the first two model years after the shift. However, a fair number of models had a "transitional" model year between low and high ABS-installation rates. So as not to lose these models from the analysis, they are included, skipping the transition year and keeping the two years before and after it.

Table 2-1 lists the 60 models contributing data to the analyses, the range of model years included in each case, and the proportion of cars equipped with ABS before and after the shift. The identification of makes and models in the FARS data is based on decoding the VIN. Since 1991, NHTSA staff has maintained a series of VIN analysis programs for use in evaluations. The programs are available to the public.

A unique advantage of performing the evaluation in 2009 rather than 10 years earlier is that a fair number of models recently shifted from high to low installation rates – either by dropping standard ABS and making it optional, or because fewer consumers purchased the option. These models are shown in red on Table 2-1. They help "balance" the analysis because, for these models, the newer cars are the ones with less ABS. The analysis actually captures some high-sales GM models twice: when ABS became standard in the 1990s and when it became an option after 2000.

[48] *Ward's Automotive Yearbooks*,; Kahane (1994), Appendix A.

TABLE 2-1: PASSENGER CARS RECEIVING OR LOSING ABS
MAKES, MODELS AND MODEL YEARS INCLUDED IN THE ANALYSIS
(Bold model names: 1 model year gap between "pre" and "post" or elsewhere)

	Limited or No ABS		Standard or High % ABS		
Make and Model	**MY**	**% ABS**	**MY**	**% ABS**	**Pct Pt Change**
Chrysler Sebring Coupe	1998-99	28%	1995-96	100%	72%
Chrysler Cirrus/Sebring Sedan	2001-02	22%	1998-99	100%	78%
Dodge Avenger	1998-99	12%	1995-96	58%	46%
Ford Crown Victoria	1990-91	0%	1993-94	44%	44%
Lincoln Town Car	1988-89	0%	1991-92	100%	100%
Lincoln Continental	1983-84	0%	1986-87	100%	100%
Mercury Grand Marquis	1990-91	0%	1993-94	50%	50%
Mercury Sable	1991-92	23%	1994-95	79%	56%
Buick LeSabre	1990-91	3%	1993-94	100%	97%
Buick Estate/Roadmaster wagon	1989-90	0%	1991-92	100%	100%
Buick Electra	1989-90	12%	1991-92	100%	88%
Buick Riviera	1989-90	17%	1991-92	100%	83%
Buick Century	1992-93	0%	1994-95	100%	100%
Buick Century	2003-04	32%	2001-02	100%	68%
Buick Skylark	1990-91	0%	1992-93	100%	100%
Buick Regal	1990-91	4%	1993-94	79%	75%
Cadillac DeVille excl Fleetwood	1989-90	0%	1991-92	100%	100%
Cadillac Fleetwood FWD	1987-88	0%	1989-90	100%	100%
Cadillac Fleetwood Brougham	1988-89	0%	1991-92	100%	100%
Cadillac Eldorado	1988-89	13%	1991-92	100%	87%
Chevrolet Caprice Sedan	1989-90	0%	1991-92	100%	100%
Chevrolet Caprice wagon	1989-90	0%	1991-92	100%	100%
Chevrolet Corvette	1984-85	0%	1986-87	100%	100%
Chevrolet Cavalier	1990-91	0%	1992-93	100%	100%
Chevrolet Cavalier	2003-04	34%	2001-02	100%	66%
Chevrolet Corsica/Beretta	1990-91	0%	1992-93	100%	100%
Chevrolet Lumina	1990-91	0%	1992-93	62%	62%
Chevrolet Malibu/Classic	2004-05	13%	2001-02	100%	87%
Oldsmobile Delta 88	1990-91	5%	1993-94	100%	95%
Oldsmobile Custom Cruiser	1989-90	0%	1991-92	100%	100%
Oldsmobile 98	1989-90	9%	1991-92	100%	91%
Oldsmobile Toronado	1988, 1990	11%	1991-92	100%	89%
Oldsmobile Ciera	1992-93	0%	1994-95	100%	100%
Oldsmobile Cutlass Supreme	1991-92	17%	1994-95	100%	83%
Oldsmobile Calais/Achieva	1990-91	1%	1992-93	100%	99%
Oldsmobile Alero	2003-04	25%	2001-02	100%	75%

TABLE 2-1 (continued): PASSENGER CARS RECEIVING OR LOSING ABS
MAKES, MODELS AND MODEL YEARS INCLUDED IN THE ANALYSIS
(Bold model names: 1 model year gap between "pre" and "post" or elsewhere)

	Limited or No ABS		Standard or High % ABS		
Make and Model	**MY**	**% ABS**	**MY**	**% ABS**	**Pct Pt Change**
Pontiac Sunbird	1990-91	0%	1992-93	100%	100%
Pontiac Sunfire	2003-04	20%	2001-02	100%	80%
Pontiac Grand Am	1990-91	1%	1992-93	100%	99%
Pontiac Grand Am	2004-05	27%	2001-02	100%	73%
Saturn L sedan	2001-02	21%	2004-05	100%	79%
VW Jetta	1997-98	12%	1999-00*	100%	88%
VW Golf	1997-98	33%	1999-00*	100%	67%
VW Passat	1993-94	18%	1995-96	78%	60%
BMW 300	1984-85	0%	1986-87	100%	100%
BMW 500	1983-84	0%	1986-87	100%	100%
BMW 600	1983-84	0%	1985-86	100%	100%
BMW 700	1983-84	0%	1985-86	100%	100%
Nissan Maxima	1998-99	35%	2001-02	100%	65%
Honda Accord	1990-91	3%	1993-94	49%	46%
Jaguar XJ sedan	1986-87	0%	1988-89	100%	100%
Jaguar XJ-S coupe	1987-88	0%	1989-90	100%	100%
Mercedes basic sedan	1984-85	0%	1986-87	100%	100%
Mercedes SDL/SEL/SEC/SD/SE	1983-84	0%	1985-86	100%	100%
Saab 900	1988-89	0%	1990-91	100%	100%
Saab 9000	1986-87	0%	1988-89	100%	100%
Subaru Legacy/Outback	1994-95	35%	1996-97	95%	60%
Toyota Camry	1991-92	17%	1994-95	82%	65%
Toyota Avalon	1995-96	26%	1997-98	100%	74%
Volvo 240	1989-90	0%	1991-92	100%	100%
Grand Average		**7%**		**88%**	**81%**

*After redesign

As stated above, crash experience for the low- and high-ABS cars should be from the same calendar years. Many of the models in Table 2-1 have model-year ranges that end before 1995, in some cases well before 1995. For those models, all FARS cases from CY 1995 to 2007 are included. For the other models, FARS data are included beginning only with the last model year in the range. For example, the model year ranges for Chrysler Sebring Coupe are 1995 to 1996 and 1998 to 1999; only FARS data from calendar years 1999 to 2007 are included, because those are the only calendar years where the full model-year range of vehicles is represented.

Three sporty models with high sales – Chevrolet Camaro, Pontiac Firebird, and Ford Mustang – are omitted from the study. Their drivers have high rates of run-off-road crashes. That might confound the analyses of the possible effect of ABS on those crashes.

For the 60 makes and models combined, 6.8 percent of the cars in the low-ABS model-year range were equipped with ABS; 88.2 percent of the cars in the high-ABS model years had ABS. That is an 81.4 percentage-point gain in the share of cars equipped with ABS. These percentages are a weighted average of Ward's percent of ABS installation for each make, model, and model year. The weight factors are the sums of registration years for each make, model, and model year over the calendar years that FARS data are included in the study. Registration years are based on R.L. Polk's National Vehicle Population Profile.

The analysis file includes 38,251 FARS cases of cars involved in crashes, ample data for statistical analyses. By contrast, NHTSA's 1994 evaluation was based on 3,703 FARS cases.

2.1.4 Adjusting the case counts for air-bag effectiveness

The great influx of ABS in high-sales makes and models was concentrated in the early 1990s, as shown in Table 2-1. It so happened that most cars also received frontal air bags in the early 1990s, often in the same year as ABS. Among the 60 makes and models included in Table 2-1:

- During the low-ABS model years, 73 percent of the cars had no air bags, 15 percent driver-only air bags, and 12 percent dual air bags.
- Whereas during the high-ABS model years, 28 percent had no air bags, 35 percent driver-only, and 37 percent dual.

Air bags save lives in frontal impacts. If the analysis failed to adjust for the effect of air bags, it would spuriously attribute a reduction of frontal fatal crash involvements to ABS, when that reduction is in fact due to the air bags changing the crashes from fatal to nonfatal. NHTSA's statistical analyses of FARS estimate that frontal air bags reduce fatality risk in frontal crashes, but substantially more so when the principal impact point, IMPACT2 = 12 (front-center or front-distributed) than when it is 11 or 1 (front-corner). Air bags are also slightly more effective for adult passengers than for drivers, and for unbelted than for belted occupants.[49]

[49] Kahane (2004), pp. 108-113 and 311-312.

Estimated Fatality Reduction (%) By Air Bags in Frontals

	Belted Occupants	Unbelted Occupants
IMPACT2 = 12		
Drivers	25	33
RF passengers age 13+	28	36
IMPACT2 = 11 or 1		
Drivers	13	17
RF passengers age 13+	15	19

FARS case counts in the analyses will be weighted upward, when appropriate, by dividing by one minus fatality reduction. For example, in a crash involvement with IMPACT2 = 12 in which the belted driver of the case vehicle is the only fatality in the entire crash (FATALS = 1), that case receives a weight factor of 1/(1 - .25) = 1.333. The rationale is that if 1,000 such cases actually existed on FARS, there would have been 1,333 such cases if the cars had not been equipped with air bags, because the air bags saved 333 lives (25% of 1,333). As a result those crash involvements became nonfatal and never appeared on FARS. But they would have appeared on FARS if those cars had been equipped only with ABS and not air bags.

Cases are not weighted upward – i.e., have a weight factor of just 1.000 when:

- The case car is not equipped with air bags
- The crash is fatal to anybody other than the driver and right-front passenger of the case car – e.g., a back-seat occupant, a pedestrian, or an occupant of another vehicle – because that crash would continue to be in FARS whether or not the air bags saved the driver or right-front passenger
- The crash is fatal only to the right-front passenger, but the car only has a driver air bag, or the passenger is less than 13 years old
- IMPACT2 is not 1, 11, or 12, or
- The crash is a first-event rollover or other non-collision (HARM_EV = 1-6)

The vast majority of cases have a weight factor of 1.000. Overall, the 38,251 actual FARS cases amount to a weighted total of 39,625. The case "counts" in the basic analysis of the overall effect of ABS will add up to 39,625.

One downside of weighting the cases is that chi-square (χ^2) statistics for contingency tables of weighted counts cannot be given their customary interpretation of significance. That would have required the tables to be filled with unweighted data derived from a simple random sample. The next section explains the procedures for measuring sampling error and testing significance.

2.1.5 Results

Table 2-2 shows the actual and weighted case counts for each analysis of the effect of ABS in passenger cars, the effectiveness estimates, the significance-test results and the confidence bounds. Here is how the statistics are derived for the basic estimate of the effect of ABS in all non-control-group crashes on all roads.

The 2x2 contingency table of actual case counts for the entire database is:

	Cars with 7% ABS	Cars with 88% ABS
Control group involvements	5,404	5,654
All non-control-group involvements	13,478	13,715

The observed effect is:

$$1 - [(13{,}715/5{,}654) / (13{,}478/5{,}404)] = 2.74 \text{ percent reduction}$$

However, the calculation based on actual case counts exaggerates the benefits of ABS because it does not adjust for the effect of air bags being introduced more or less simultaneously with ABS. The 2x2 table of case counts weighted upwards for the effect of air bags is:

	Cars with 7% ABS	Cars with 88% ABS
Control group involvements	5,467	5,808
All non-control-group involvements	13,809	14,542

Weighting the cases increases each cell count in the contingency table. However, the increase is proportionally larger for cars with ABS because they have more air bags. It is also larger for response-group involvements, because a larger portion of them is frontal (many control-group cases are rear impacts). That shrinks effectiveness. The observed effect is now only:

$$1 - [(14{,}452/5{,}808) / (13{,}809/5{,}467)] = 0.87 \text{ percent reduction}$$

That estimate is rounded to 1 percent and shown in the fifth column of the “all non-control-group crashes” row of Table 2-2. But that is the effect of increasing the market share of ABS from 6.8 percent to 88.2 percent. The effect of increasing all the way from zero ABS to 100 percent ABS would be higher:

$$\{1 - [(14{,}452/5{,}808) / (13{,}809/5{,}467)]\} / \{.882 - .068 \times [(14{,}452/5{,}808) / (13{,}809/5{,}467)]\}$$

$$= 1.08 \text{ percent reduction}$$

Table 2-2: Passenger Cars, Distribution of Fatal Crash Involvements with and Without 4-Wheel ABS, FARS 1995-2007

	Actual FARS Case Counts		Air-Bag-Weighted N		Fatal Crash Reduction (%)		t for H_0: Red. = 0	90% Confidence Bounds	
	Cars w 7% ABS	Cars w 88% ABS	Cars w 7% ABS	Cars w 88% ABS	88% vs. 7% ABS	100% vs. no ABS		Lower	Upper
Control group involvements	5,404	5,654	5,467	5,808					
ALL ROADS									
All non-control-group involvements	13,478	13,715	13,809	14,542	1	1	.45	-3	5
All crash involvements						1		-2	4
Run-off-road crashes	4,631	5,024	4,784	5,435	-7	**-9**	**2.65**	**-15**	**-3**
Side impacts w fixed objects	748	978	751	988	-24	**-30**	**4.15**	**-46**	**-16**
First-event rollovers	705	815	705	815	-9	-11	1.44	-26	3
Other run-off-road crashes	3,178	3,231	3,328	3,631	-3	-3	.88	-11	3
Pedestrian/bicyclist/animal	1,683	1,593	1,684	1,596	11	**13**	**2.99**	**5**	**20**
Culpable involvements w other veh	5,975	5,939	6,130	6,306	3	4	1.61	-1	8
WET, SNOWY, OR ICY ROADS									
All non-control-group involvements	3,144	3,273	3,207	3,434	-1	-1	.26	-8	6
All crash involvements						-1		-7	5
Run-off-road crashes	738	954	762	1,031	-27	**-34**	**4.90**	**-50**	**-20**
Side impacts w fixed objects	160	280	161	282	-65	**-85**	**5.21**	**-130**	**-49**
First-event rollovers	73	109	73	109	-41	**-52**	**1.95**	**-125**	**-2**
Other run-off-road crashes	505	565	528	640	-14	**-17**	**2.25**	**-34**	**-3**
Pedestrian/bicyclist/animal	230	244	231	244	none	none	.02	-23	19
Culpable involvements w other veh	1,224	1,141	1,249	1,198	10	**12**	**2.43**	**3**	**20**

That estimate, although somewhat higher, still rounds to 1 percent, and it is shown in the sixth column of Table 2-2, the column headed by "100% versus no ABS." It is the basic point estimate of the effect of ABS.

Statistical significance of the fatality reductions cannot be tested with simple 2x2 chi-squares of the cell counts, because they are weighted counts, not actual numbers of cases. Some FARS cases have been weighted more than 1 to adjust for the effect of air bags. Instead, the FARS data are split up into 10 systematic random subsamples. The last digit of the case identification number ST_CASE are useful for splitting FARS into systematic random subsamples. Thanks to the ample data available, effectiveness can be calculated separately in each subsample and significance tested by observing the variation of the estimate across the 10 subsamples.

However, the variance estimate obtained by running through the procedure just once could be too high or too low by chance, depending on what cases happened to get into the 10 subsamples. A second iteration of the same procedure, but with FARS split up into subsamples in a different way, might generate a lower or higher estimate. Numerous iterations, each with a different splitting of FARS into subsamples, will generate a range of variance estimates, and the median of these estimates will be used. Specifically, the last two digits of ST_CASE were used to subdivide FARS into 100 groups (numbered 0 to 99). The numbers 0 to 99 were randomly re-ordered by a SAS random-number generator and listed in the new order. The FARS cases whose last two ST_CASE digits were among the first 10 on the new list became subsample 1, the next 10 became subsample 2, and so on. After these 10 subsamples were created, the numbers 0 to 99 were randomly reordered anew and another set of 10 subsamples was created. In all, the procedure was repeated 11 times and it created 11 sets of 10 subsamples each.

It is easier to work with the effect of increasing the market share of ABS from 6.8 percent to 88.2 percent than with the effect of increasing all the way from zero ABS to 100 percent ABS. The former can be expressed as a log-odds-ratio, which tends to have a normal distribution. If the former effect is significant, the latter will be, too.

Based on the weighted cell counts, the effect of increasing the market share of ABS from 6.8 percent to 88.2, estimated for the entire FARS database, may be expressed as a log-odds ratio:

$$\log r = \log [(14{,}452/5{,}808) / (13{,}809/5{,}467)] = -.0088$$

On the first of the 11 times that FARS was split into 10 subgroups, subgroup 1 happened to consist of cases with ST_CASE ending in 01, 05, 06, 21, 23, 27, 38, 61, 65, or 81. For these cases, the corresponding log-odds ratio is:

$$\log r = \log [(1{,}522/598) / (1{,}432/566)] = +.0058$$

For subgroup 2, on the other hand, log r = -.0767; for subgroup 3, log r = -.0018; and so on. The standard deviation of ten estimates for the 10 mutually exclusive subgroups, each based on a different tenth of the FARS data is .0558. The standard deviation S_1 of the corresponding estimate of log r in the full dataset (10 times as many cases) is $.0558 / \sqrt{10} = .0176$. This is the estimated standard deviation of log r, for the full dataset, based on our first run-through of splitting FARS into 10 systematic random subsamples.

On the second iteration, the estimate of the standard deviation S_2, derived from the 10 subsamples created on that iteration, was slightly higher, .0228. On the third iteration, S_3 = .0182. Over all 11 iterations, the estimates S_j ranged from .0092 to .0319. However, the median of these 11 estimates is S = .0198, which was the value obtained on the eighth iteration. (In fact, except for the low and high estimates generated on the 4th and 9th iterations, the remaining S_j are all quite close to the median.)

For the full dataset, log r was -.0088. Because t = |log r| / S = .0088 / .0198 = .45 is less than 1.833 (the 95th percentile of a t-distribution with 9 degrees of freedom[50]), the observed fatal-crash reduction for ABS is not statistically significant at the one-sided .05 level.

The 90 percent confidence bounds for the effect of increasing all the way from zero ABS to 100 percent ABS are:

$$\{1 – [1 - \exp (\log r \pm 1.833 \times S)]\} / \{.882 – .068 \times [1 - \exp (\log r \pm 1.833 \times S)]\}$$

$$= \{1 – [1 - \exp (–.0088 \pm 1.833 \times .0198)]\} / \{.882 – .068 \times [1 - \exp (–.0088 \pm 1.833 \times .0198)]\}$$

= from a 3-percent increase to a 5 percent reduction

The seventh column of Table 2-2 shows the t value for the effectiveness estimate of ABS. The two right columns show the lower and upper 90 percent confidence bounds for the effect of ABS – i.e., the shift from no ABS to 100% ABS.

Now let us discuss the point and interval estimates for all the crash types in Table 2-2. Positive estimates (reductions in fatal crashes with ABS, relative to the control group) are shown in black, negative estimates in red. Statistically significant point estimates are printed bold, and they are shaded light-blue if positive, yellow if negative. Non-significant estimates are not printed bold, and have a negative lower confidence bound and a positive upper bound.

The effect of ABS on all crashes, including the control-group crashes where we assume it has no effect, is derived from the preceding estimate. Without ABS, there were 5,467 weighted control-group involvements and 13,809 response group involvements. The point estimate for all response-group crashes is a 1.08 percent reduction. The point estimate for all crashes is:

[13,809 / (5,467 + 13,809)] x 1.08 = 0.77 percent reduction

Its 90 percent confidence bounds, similarly derived, are from -2 to +4 percent: a negligible overall effect.

But ABS does have statistically significant effects in some types of crashes. Run-off-road crashes increase by a statistically significant 9 percent. The t value is 2.65, significant at the one-sided .05 level (because it exceeds 1.833) and, for that matter, even at the two-sided .05 level (because it exceeds 2.262, the 97.5th percentile of t with 9 df). Whereas the effect has diminished since calendar years 1989-1993 (a 28% increase in run-off-road crashes, according to NHTSA's

[50] Because each s_j is calculated by computing the variance of 10 observations (log r for each of 10 subgroups), it is appropriate to use a t test with 9 df to test if log r is significantly different from zero.

initial evaluation[51]), it continues to be negative and statistically significant. The observed effect might have diminished over time because more drivers knew how to use ABS properly (in part thanks to public information campaigns), or because the technology was refined, or by chance alone – but a residual significant effect still remains.

Furthermore, all three subsets of run-off-road crashes were observed to increase with ABS. The largest increase and the only statistically significant one is side impacts with fixed objects, increasing by 30 percent (t = 4.15; confidence bounds, 16% to 46% increase). Rollovers increased by a non-significant 11 percent, other run-off-road crashes (mostly frontal impacts with fixed objects), by 3 percent.

By contrast, ABS is associated with reductions of crashes that generally do not involve running off the road. Fatal collisions with pedestrians, bicyclists or animals decrease by a statistically significant 13 percent (t = 2.99). Most of these collisions involve hitting a non-motorist or animal on the road, rather than first running off the road and then hitting a non-motorist. Culpable involvements in collisions with other vehicles decreased by 4 percent, but the reduction falls short of statistical significance (t = 1.61).

Almost every one of the effects is magnified on wet, snowy, or icy roads, where ABS is much more likely to activate. The net effect on these roads is negligible, but the increase in run-off-road crashes is a statistically significant 34 percent. Moreover, the increase is statistically significant in all three subsets of run-off-road crashes, reaching 85 percent in side impacts with fixed objects. The harm in run-off-road crashes is offset by benefits in collisions with other vehicles, including a significant 12 percent reduction of culpable involvements in these collisions. The only inconsistent result is a zero effect on collisions with pedestrians, bicyclists, and animals; it raises a question about the significant benefit seen on all (i.e., dry) roads.

On dry roads, the overall increase in run-off-road crashes is a fairly negligible 4 percent; it is not statistically significant (t = 1.07). However, side impacts with fixed objects increased by a statistically significant 16 percent (t = 2.35). The reduction in fatal collisions with pedestrians, bicyclists, and animals on dry roads is a statistically significant 15 percent (t = 3.21). It is not clear why ABS should be so effective in pedestrian crashes on dry roads. Perhaps, as drivers become used to having ABS, they have become more willing to take immediate, decisive action if a pedestrian suddenly materializes in front of them: stomp and stay on the brakes, and steer.

2.1.6 Comparative results for four cohorts of cars

A relatively small number of high-sales General Motors models that received ABS as standard equipment in the early 1990s predominated the databases of the early evaluations of ABS (Buick Park Avenue; Cadillac DeVille; Chevrolet Caprice, Cavalier, and Corsica; Pontiac Grand Am; and similar cars). The observed increases of run-off-road crashes in those studies might be critiqued as somehow attributable to those specific models. For example, a change in the models unrelated to ABS that made them appear sportier or with greater appeal in rural markets could have increased run-off-road crashes relative to other types. Or it might have been the specific

[51] Kahane (1994), pp. xi and 95.

ABS technology in those models. (That is in addition to the more generic critique that drivers were initially not aware of how to use ABS.)

By 2009, a much more representative list of models, as shown in Table 2-1, is available, especially if the models with standard ABS are supplemented by those sold with a high percentage of optional ABS. The models in Table 2-1 can be grouped into four cohorts and the effect of ABS estimated separately in each one:

- GM models that had a high percentage of ABS by 1993.
- Non-GM models that had a high percentage of ABS by 1993. Ford products and Honda Accord predominate.
- Models that received a high share of ABS after 1993. Includes high-sales models such as VW Jetta, Nissan Maxima, Subaru Legacy, Toyota Camry, and Toyota Avalon.
- Models that dropped standard ABS, or where optional ABS lost a substantial share of the market: Chrysler and GM cars, including many of the GM models in the first cohort, but 10 model years later.

Table 2-3 shows the point estimates for the effect of ABS in each cohort of cars for five "bellwether" types of crashes:

TABLE 2-3

OBSERVED PERCENT FATALITY REDUCTION FOR ABS
BY CAR COHORT AND CRASH TYPE

Crash Type	GM ABS by 1993	Non-GM ABS by 1993	Added ABS 1994+	Dropped ABS[52]
Run-off-road	- 9	- 7	none	- 13
Run-off-road, wet-snowy-icy	- 28	- 39	- 21	- 22
Side impact with fixed object	- 24	- 34	- 14	- 33
Pedestrian/bicyclist/animal	18	9	8	- 6
Culpable w other veh, wet-snowy-icy	14	7	13	- 18

The observed effect on run-off-road crashes is never positive and it is negative in three of the four cohorts. Run-off-road crashes in wet, snowy, or icy conditions and side impacts with fixed objects in any conditions increased substantially and consistently with ABS in every cohort. The effect is not a quirk of the early 1990s or the particular ABS technology in use at that time.

[52] In this cohort, effect for each response group was measured relative to vehicle registration years rather than control-group involvements. There were unexpectedly few control-group involvements in the ABS-equipped cars.

Indeed, GM models apparently increased run-off-road crashes when they acquired ABS in the early 1990s and then reduced run-off-road crashes when they dropped ABS after 2000. Conversely, pedestrian crashes decreased with ABS in three of the four cohorts, as did culpable involvements with other vehicles on wet, snowy, or icy roads.

2.1.7 Drinking versus non-drinking drivers

Harless and Hoffer presented analyses in 2002 asserting that the increase in run-off-road crashes with ABS was primarily confined to drinking drivers, and that non-drinking drivers experienced little or no increase in run-off-road crashes.[53] Their analyses further showed the increase for drinking drivers was limited to calendar years 1993 to 1995, when the GM cars that had received standard ABS were 2 to 4 years old, and was non-significant in later years. The database for this report makes it possible to compare statistics for drinking and non-drinking drivers from 1995 through 2007, and also to look at cars other than the GM models of the early 1990s.

For our analysis, let us define "non-drinking drivers" to be those whose BAC was reported to be .00, plus those whose BACs were not reported but whom police reported as not drinking (DRINKING = 0). "Drinking drivers" are those with BACs reported and at least .02 g/dL, plus those with unreported BACs but police-reported drinking (DRINKING = 1). All other drivers, including those with BACs = .01 are excluded. If entirely separate analyses are performed for non-drinking and drinking drivers, including control groups drawn only from these drivers, the increase in run-off-road crashes indeed seems at first glance limited to the drinking drivers (54% increase), with even a 1 percent reduction for the non-drinkers:

With Separate Control Groups	Cars with 7% ABS	Cars with 88% ABS	Reduction for ABS (%)
	Non-Drinking Drivers		
Control group	4,058	4,456	
Run-off-road	2,055	2,234	1
	Drinking Drivers		
Control group	272	205	
Run-off-road	2,014	2,336	- 54

While this is a logically defensible analysis, the cell counts in the table are not reasonable. The numbers of run-off-road crashes, both with and without ABS, are similar for the non-drinkers and the drinkers, but the control group is almost 20 times as large for the non-drinkers. Even that is reasonable, because drinking drivers are at much higher risk and are usually culpable for the crashes they get into. What is not plausible is that there are 272 control-group crashes without

[53] Harless, D. W.,& Hoffer, G. E. (2002, May). The antilock braking system anomaly: a drinking driver problem? *Accident Analysis and Prevention*, Vol. 34, , pp. 333-341.

ABS and only 205 with ABS. If control-group involvements are a surrogate for "exposure," this says that the cars without ABS have far more exposure for drinking drivers than cars with ABS – even though for non-drinking drivers the exposure is about the same. In other words, drivers drink much less when their cars are equipped with ABS. But that is unlikely. The cars with ABS are the same makes and models as the cars without ABS, observed in the same calendar years, with just two years difference in vehicle age (mostly newer, sometimes older). There is every reason to believe drinking would be about the same. The reduction of control group crashes from 272 to 205 is most likely a chance event. It is something that could occasionally happen by chance with numbers this small. It would almost certainly not have happened if the numbers had been in the thousands. It is the drop from 272 to 205 that is "driving" the results.

If, instead, the same control group is used for the non-drinking and drinking drivers, namely the weighted counts for all cases as shown in Table 2-2, the effects on run-off-road crashes are much closer:

With Joint Control Group	Cars with 7% ABS	Cars with 88% ABS	Reduction for ABS (%)
	Non-Drinking Drivers		
Control group (from Table 2-2)	5,467	5,808	
Run-off-road	2,055	2,234	- 2
	Drinking Drivers		
Control group (from Table 2-2)	5,467	5,808	
Run-off-road	2,014	2,336	- 9

A similar result is obtained if run-off-road crashes are analyzed relative to exposure in vehicle registration years, rather than relative to a control group:

Relative to Vehicle Registration Years	Cars with 7% ABS	Cars with 88% ABS	Reduction for ABS (%)
	Non-Drinking Drivers		
Vehicle Years	86,635,000	90,374,000	
Run-off-road	2,055	2,234	- 4
	Drinking Drivers		
Vehicle Years	86,635,000	90,374,000	
Run-off-road	2,014	2,336	- 11

Whereas the last two analyses greatly shrink the absolute gap between non-drinking and drinking drivers, the results are ambiguous. They are statistically compatible with the hypothesis that the effect is the same for drinkers and non-drinkers, but also compatible with Harless and Hoffer's hypothesis that the effect is zero for non-drinkers. A clearer picture emerges when the analysis is limited to run-off-road crashes on wet, snowy, or icy roads, where ABS is much more likely to activate and its negative effect is larger:

	Cars with 7% ABS	Cars with 88% ABS	Reduction for ABS (%)
	Non-Drinking Drivers		
Control group (from Table 2-2)	5,467	5,808	
Run-off-road, wet-snowy-icy	369	486	- 23
	Drinking Drivers		
Control group (from Table 2-2)	5,467	5,808	
Run-off-road, wet-snowy-icy	296	397	- 26

The observed effect is almost identical for non-drinking drivers (23% increase) and drinking drivers (26% increase). The negative effect on run-off-road crashes does not appear to be limited to drinking drivers and it has persisted over time. Frankly, this result is more convincing than the conclusion of Harless and Hoffer. While it could be argued that drinking drivers are especially befuddled by ABS and unlikely to use wisely the capability to steer while braking, a probably stronger case can be made that a large proportion of the run-off-road crashes of drinking drivers do not involve braking at all and could not have been influenced by ABS.

2.1.8 Net effect by specific road-surface condition

Table 2-4 indicates that the net effect of ABS is about the same on dry, wet, snowy, and icy roads. The observed net effect is close to zero in each road condition.

TABLE 2-4

NET EFFECT OF ABS, BY ROAD-SURFACE CONDITION

	Air-Bag-Weighted N		
	Cars w 7% ABS	Cars w 88% ABS	Fatal Crash Reduction (%)
Control group involvements	5,467	5,808	
All non-control-group involvements on:			
Dry roads	10,502	11,024	1
Wet roads	2,630	2,797	none
Snowy or slushy roads	304	346	- 7
Icy roads	273	291	none

2.2 Analysis of rear-wheel ABS for LTVs

Almost all GM, Ford, and Dodge pickup trucks and most of their SUVs received ABS for the rear wheels only as standard equipment in the late 1980s or by 1990; many vans and foreign-based-nameplate LTVs shortly thereafter. Four-wheel ABS usually did not arrive on LTVs until at least several model years later. The analysis of rear-wheel ABS for LTVs closely parallels the procedures described in Section 2.1, addressing four-wheel ABS for passenger cars. Here, too, the analysis is based on FARS data for calendar years 1995 to 2007. The control group and response group of crash involvements are defined exactly as in Section 2.1.2. The control group consists of LTVs that were stopped, parked, backing, moving slower than 10 mph, parking, or leaving a parking place when they were hit; or were struck in the rear; or were non-culpable parties to a collision involving two or more vehicles.

2.2.1 LTVs without ABS versus LTVs with rear-wheel ABS

Most LTV models changed from not offering ABS at all in one model year to having rear-wheel ABS as standard equipment the next year. Rear-wheel ABS was rarely an option. The analysis will include one model that shifted from optional to standard ABS and an adjustment factor to translate the observed effect to the effectiveness of changing from 0 to 100 percent ABS.

NHTSA's 1993 evaluation report (based on information furnished by the manufacturers or from news articles) and *Ward's Automotive Yearbooks* document what LTVs had rear-wheel ABS.[54]

Table 2-5 lists the 31 models contributing data to the analyses, the range of model years included in each case, and the proportion of LTVs equipped with rear-wheel ABS before and after the shift (0% and 100%, respectively, except for the Nissan pickup). The identification of makes and models in the FARS data is based on decoding the VIN. Unlike the database for passenger cars, there are no LTV models that dropped from standard to no ABS or with a "transitional" model year between low and high installation rates. But four models will be included for only a single year without ABS (1988) and a single year with rear-wheel ABS (1989), because they already began to offer four-wheel ABS in the next year (1990).

All models in Table 2-5 except the Nissan pickup have model-year ranges that end before 1995 and all FARS cases from CY 1995 to 2007 will be included for those models. For the Nissan pickup, the model year range extends to 1996; only FARS data from 1996 to 2007 will be included. For the 31 makes and models combined, 1.2 percent of the LTVs in the low-ABS model-year range were equipped with ABS; 100 percent of the LTVs in the high-ABS model years had rear-wheel ABS. That is a 98.8 percentage-point gain in the share of LTVs equipped with rear-wheel ABS.

The analysis file includes 26,324 FARS cases of LTVs involved in crashes. By contrast, NHTSA's 1993 evaluation was based on 9,621 FARS cases.

[54] Kahane, C.J. (1993). *Preliminary Evaluation of the Effectiveness of Rear-Wheel Antilock Brake Systems for Light Trucks*. NHTSA Docket No. 70-27-GR-026, p. 15. Washington, DC: National Highway Traffic Safety Administration; *Ward's Automotive Yearbooks*.

TABLE 2-5: LTVs RECEIVING REAR-WHEEL ABS
MAKES, MODELS AND MODEL YEARS INCLUDED IN THE ANALYSIS

	Limited or No ABS		Standard or High % Rear-Wheel ABS		
Make and Model	**MY**	**% ABS**	**MY**	**% ABS**	**Pct Pt Change**
Dodge Dakota	1987-88	0%	1989-90	100%	100%
Dodge D/W pickup	1987-88	0%	1989-90	100%	100%
Dodge Ramcharger	1988-89	0%	1990-91	100%	100%
Dodge Ram van and wagon	1988-89	0%	1990-91	100%	100%
Ford Ranger pickup	1987-88	0%	1989-90	100%	100%
Ford F pickup	1985-86	0%	1987-88	100%	100%
Ford Bronco 2	1985-86	0%	1987-88	100%	100%
Ford Bronco	1985-86	0%	1987-88	100%	100%
Ford Aerostar van and wagon	1988-89	0%	1990-91	100%	100%
Ford big van	1988-89	0%	1990-91	100%	100%
Chevrolet S/T pickup	1987-88	0%	1989-90	100%	100%
Chevrolet C/K pickup	1986-87	0%	1988-89	100%	100%
Chevrolet S/T Blazer	1988	0%	1989	100%	100%
Chevrolet V Blazer	1988-89	0%	1990-91	100%	100%
Chevrolet Suburban	1988-89	0%	1990-91	100%	100%
Chevrolet Astro wagon/van	1988	0%	1989	100%	100%
Chevrolet big van	1988-89	0%	1990-91	100%	100%
Chevrolet Geo Tracker	1989-90	0%	1991-92	100%	100%
GMC Sonoma pickup	1987-88	0%	1989-90	100%	100%
GMC C/K pickup	1986-87	0%	1988-89	100%	100%
GMC S/T Jimmy	1988	0%	1989	100%	100%
GMC V Jimmy	1988-89	0%	1990-91	100%	100%
GMC Suburban	1988-89	0%	1990-91	100%	100%
GMC Safari wagon/van	1988	0%	1989	100%	100%
GMC big van	1988-89	0%	1990-91	100%	100%
Nissan pickup	1993-94	27%	1995-96	100%	73%
Nissan Pathfinder	1989-90	0%	1991-92	100%	100%
Isuzu pickup	1989-90	0%	1991-92	100%	100%
Mazda pickup	1989-90	0%	1991-92	100%	100%
Mazda MPV	1989-90	0%	1991-92	100%	100%
Suzuki Sidekick 2dr	1989-90	0%	1991-92	100%	100%
Grand Average		**1%**		**100%**	**99%**

2.2.2 Results

Table 2-6 shows the actual case counts for each analysis of the effect of rear-wheel ABS in LTVs, the effectiveness estimates, the significance-test results and the confidence bounds. Except for the Nissan pickup, accounting for a small portion of the database, none of the models in Table 2-5 were equipped with frontal air bags during the model years included in the data. Unlike Section 2.1.4, it is unnecessary to weight the cases for the effect of air bags. Effectiveness estimates may be derived from the actual case counts. The 2x2 contingency table for the entire database is:

	LTVs with 1% ABS	LTVs with 100% ABS
Control group involvements	3,577	4,185
All non-control-group involvements	8,722	9,840

The observed effect is:

$$1 – [(9{,}840/4{,}185) / (8{,}722/3{,}577)] = 3.57 \text{ percent reduction}$$

That estimate is rounded to 4 percent and shown in the third column of the “all non-control-group crashes” row of Table 2-6. But that is the effect of increasing the market share of rear-wheel ABS from 1.2 percent to 100 percent. The effect of increasing all the way from zero ABS to 100 percent ABS would be just slightly higher:

$$\{1 – [(9{,}840/4{,}185) / (8{,}722/3{,}577)]\} / \{1.000 – .012 \times [((9{,}840/4{,}185) / (8{,}722/3{,}577))]\}$$

$$= 3.61 \text{ percent reduction}$$

That estimate still rounds to 4 percent and it is shown in the fourth column of Table 2-6, the column headed by “100% versus no ABS.” It is the basic point estimate of the effect of rear-wheel ABS.

The t-tests for statistical significance of the point estimates and the estimation of 90 percent confidence bounds are based on the same procedure as for passenger cars (Section 2.1.5). The t value for the preceding point estimate is 1.34. Because that is less than 1.833 (the 95th percentile of a t-distribution with 9 degrees of freedom[55]), the observed fatal-crash reduction for rear-wheel ABS is not statistically significant at the one-sided .05 level. The 90 percent confidence bounds for effectiveness range from a 1-percent increase to an 8 percent reduction in fatal crash involvements. The t values and confidence bounds are shown in the last three columns of Table 2-6.

[55] See Section 2.1.5.

Table 2-6: LTVs, Distribution of Fatal Crash Involvements With and Without Rear-Wheel ABS, FARS 1995-2007

	Actual FARS Case Counts		Fatal Crash Reduction (%)		t for H_0: Red. = 0	90% Confidence Bounds	
	LTVs w 1% ABS	LTVs w 100% ABS	100% vs. 1% ABS	100% vs. no ABS		Lower	Upper
Control group involvements	3,577	4,185					
ALL ROADS							
All non-control-group involvements	8,722	9,840	4	4	1.34	-1	8
All crash involvements						-1	6
Run-off-road crashes	3,728	4,176	4	4	1.20	-2	11
Side impacts w fixed objects	403	436	8	8	.85	-10	22
First-event rollovers	1,209	1,310	7	7	1.76	none	15
Other run-off-road crashes	2,116	2,430	2	2	.43	-6	9
Pedestrian/bicyclist/animal	1,266	1,266	14	**15**	**3.35**	**7**	**22**
Culpable involvements w other vehicle	2,795	3,239	1	1	.32	-5	6
WET, SNOWY, OR ICY ROADS							
All non-control-group involvements	2,045	2,427	-1	-1	.38	-9	5
All crash involvements				-1		-8	5
Run-off-road crashes	607	664	7	7	1.29	-3	15
Side impacts w fixed objects	90 3	89	15	16	1.01	-15	38
First-event rollovers	139	175	-8	-8	.65	-33	12
Other run-off-road crashes	378	400	10	10	1.34	-4	21
Pedestrian/bicyclist/animal		213	1	1	.05	-20	18
Culpable involvements w other vehicle	183 525	638	-4	-4	.68	-15	

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Now let us discuss the point and interval estimates for all the crash types in Table 2-6. Positive estimates (reductions in fatal crashes with ABS, relative to the control group) are shown in black, negative estimates in red. Statistically significant point estimates are printed bold, and they are shaded light-blue if positive, yellow if negative. Non-significant estimates are not printed bold, and have a negative lower confidence bound and a positive upper bound.

The effect of rear-wheel ABS on <u>all crashes</u>, including the control-group crashes where we assume it has no effect, is:

$$[8{,}722 / (3{,}577 + 8{,}722)] \times 3.61 = 2.56 \text{ percent reduction}$$

Its 90 percent confidence bounds, similarly derived, are from -1 to +6 percent.

The results for specific types of crashes are consistent with the findings of NHTSA's 1993 evaluation, which was based on FARS data from 1989 through mid-1992 (no overlap with the 1995-2007 data in this study). The only significant fatality reduction in this study was a 15 percent reduction in collisions with pedestrians, bicyclists and animals ($t = 3.35$; confidence bounds, 7% to 23%). The 1993 evaluation claimed a 5 to 15 percent reduction.[56] However, the reduction does not become stronger on wet, snowy, or icy roads, but drops to 1 percent.

Effects on run-off-road crashes never achieve statistical significance. The observed effect for all run-off-road crashes in all conditions is a 4 percent reduction ($t = 1.20$; confidence bounds, -2% to 11%). But the effects are generally positive: for all three types of run-off-road crashes on all roads, and for two out of three types on wet, snowy and icy roads. The 1993 study did not find a significant effect, either. Unlike four-wheel ABS, rear-wheel ABS does not empower drivers to steer while braking, or to misuse that capability. Rear-wheel ABS could prevent some run-off-road crashes to the extent it prevents rear-wheel lockup and resultant loss of control, but the effect in fatal crashes, if any, is not statistically detectable.

The observed reduction of culpable involvements with other vehicles was 1 percent (confidence bounds, -5% to 6%). It indicates the effect is negligible. That clarifies the conflicting results in earlier evaluations, with some analyses showing close to zero effect and others a risk increase.

The reduction in collisions with pedestrians is apparently real. It has persisted and perhaps even grown over time. The immediate goal of rear-wheel ABS is to prevent rear-wheel lockup that could result in a loss of control and lane departure. It has little effect on stopping distance or ability to steer the vehicle while braking. It is not clear why rear-wheel ABS would be directly of help if a pedestrian suddenly appears in front of the driver. Perhaps over time drivers have become acclimatized to braking immediately and aggressively as they have become less afraid that it could result in rear-wheel lockup that would be dangerous for them. That extra braking effort may be just enough to avoid hitting some pedestrians. However, by the same logic, a reduction in collisions with other vehicles might be expected, but none was observed.

[56] Kahane (1993), p. 5.

2.3 Analysis of four-wheel ABS for LTVs

Most makes and models of LTVs that were eventually equipped with four-wheel ABS first went through an intermediate stage of only rear-wheel ABS, typically for at least several years. Relatively few models went directly from no ABS to four-wheel ABS, and even fewer of those switched from little or no ABS in one model year to standard or high-percentage optional ABS in the next year. That leaves little choice except to estimate the effect of four-wheel ABS in two essentially separate steps: as the composite of the effect of switching from no ABS to rear-wheel ABS (already estimated in Section 2.2) and the effect of switching from rear-wheel to four-wheel ABS.

The analysis of switching from rear-wheel to four-wheel ABS for LTVs closely parallels the procedures addressing four-wheel ABS for passenger cars, described in Section 2.1. Here, too, the analysis is based on FARS data for calendar years 1995 to 2007. The control group and response group of crash involvements are defined exactly as in Section 2.1.2. The control group consists of LTVs that were stopped, parked, backing, moving slower than 10 mph, parking, or leaving a parking place when they were hit; or were struck in the rear; or were non-culpable parties to a collision involving two or more vehicles. Only the last part of the statistical analysis will look different: the significance tests and confidence bounds for the composite effect.

2.3.1 LTVs with rear-wheel ABS versus LTVs with four-wheel ABS

ABS might be offered on LTVs in quite a few ways. In a given model year, a make and model might offer four-wheel ABS as standard equipment, or rear-wheel ABS, or note at all. Either or both types of ABS could be options, and no ABS could also be an option. Different sub-series of the same model could have different options or standard equipment. Because the immediate goal is to compare rear-wheel and four-wheel ABS, the analysis will exclude any model year where some or all of a model run were not equipped with any ABS. *Ward's Automotive Yearbooks* document the proportions of LTVs that had rear-wheel ABS and that had four-wheel ABS in a given model year.[57]

The shift from rear-wheel to four-wheel ABS was abrupt in some models but more gradual in others, where four-wheel ABS was an option of steadily increasing popularity. For some of those models, the analysis may need to skip a "transitional" model year between mostly rear-wheel and mostly four-wheel ABS. There are no LTV models that dropped back from four-wheel to rear-wheel ABS.

Table 2-7 lists the 29 models contributing data to the analyses, the range of model years included in each case, and the proportion of LTVs equipped with four-wheel ABS before and after the shift (any LTV in Table 2-7 without four-wheel ABS has rear-wheel ABS). The identification of makes and models in the FARS data is based on decoding the VIN.

[57] *Ward's Automotive Yearbooks.*

TABLE 2-7: LTVs SWITCHING FROM REAR-WHEEL TO FOUR-WHEEL ABS
MAKES, MODELS AND MODEL YEARS INCLUDED IN THE ANALYSIS
(All these models have either rear-wheel or four-wheel ABS – none completely without ABS)
(Bold model names: 1 model year gap between "pre" and "post" or elsewhere)

	Limited or No Four-Wheel ABS		**Standard or High % Four-Wheel ABS**		
Make and Model	**MY**	**% 4-Wheel**	**MY**	**% 4-Wheel**	**Pct Pt Change**
Dodge Durango	2002-03	14%	2004-05	100%	86%
Ford Ranger	1999-2000	32%	2001-02	100%	68%
Ford F pickup	1997-98	18%	1999-2000	74%	56%
Ford Explorer	1991-92	0%	1993-94	100%	100%
Ford Bronco	1991-92	0%	1993-94	100%	100%
Ford big van/wagon	1997-98	26%	2000-01	100%	74%
Chevrolet S/T pickup	1993-94	9%	1996-97	100%	100%
Chevrolet C/K pickup	1993-94	0%	1995-96	100%	100%
Chevrolet Blazer S/T 2dr	1989-90	5%	1992-93	89%	84%
Chevrolet Blazer V/K 2dr	1991-92	0%	1993-94	100%	100%
Chevrolet Suburban	1990-91	0%	1992-93	100%	100%
Chevrolet Astro wagon	1990-91	12%	1992-93	100%	88%
Chevrolet Astro cargo van	1991-92	4%	1993-94	100%	96%
Chevrolet big van/wagon	1991-92	0%	1993-94	100%	100%
GMC Sonoma pickup	1993-94	0%	1996-97	100%	100%
GMC Sierra pickup	1993-94	0%	1995-96	100%	100%
GMC Jimmy S/T 2dr	1989-90	6%	1992-93	91%	85%
GMC Jimmy V/Yukon 2dr	1991-92	0%	1993-94	100%	100%
GMC Suburban	1990-91	0%	1992-93	100%	100%
GMC Safari wagon	1989-90	5%	1992-93	100%	95%
GMC Safari cargo van	1991-92	7%	1993-94	100%	93%
GMC big van	1991-92	0%	1993-94	100%	100%
Nissan Pathfinder	1994-95	0%	1996-97	100%	100%
Honda Passport	1996-97	20%	1998-99	100%	80%
Isuzu Trooper 4dr	1994-95	22%	1997-98	100%	78%
Isuzu Rodeo	1996-97	0%	1998-99	100%	100%
Mazda Navajo	1991-92	0%	1993-94	100%	100%
Mazda MPV	1994-95	0%	1996-97	100%	100%
Toyota 4Runner 4dr	1993-94	0%	1996-97	95%	95%
Grand Average		**8%**		**96%**	**88%**

For the models in Table 2-7 with model-year ranges that end before 1995, all FARS cases from CY 1995 to 2007 are included. For the other models, FARS data are included beginning only with the last model year in the range. For example, the model year range for Dodge Durango is 2002 to 2005; only FARS data from calendar years 2005 to 2007 are included, because those are the only calendar years where the full model-year range of vehicles will be represented.

For the 29 makes and models combined, 7.7 percent of the LTVs in the two earlier model years were equipped with four-wheel ABS (and 92.3 percent with rear-wheel ABS); 96.3 percent of the LTVs in the two later model years had four-wheel ABS (and 3.7 percent had rear-wheel ABS). That is an 88.6 percentage-point gain in the share of LTVs equipped with four-wheel ABS.

The analysis file includes 28,952 FARS cases of LTVs involved in crashes.

2.3.2 Results

The influx of four-wheel ABS in LTVs was strongest in the mid-1990s, overlapping with the introduction of frontal air bags. Among the 29 makes and models included in Table 2-7:

- During the rear-wheel-ABS model years, 25 percent of the LTVs had driver-only air bags and 6 percent dual air bags.
- Whereas during the four-wheel-ABS model years, 53 percent had driver-only air bags and 13 percent dual.

The confounding of four-wheel ABS with air bags is not quite as strong as for passenger cars, but it is strong enough that the FARS cases need to be weighted by the same procedure as in Section 2.1.4.

Table 2-8 shows the actual and weighted case counts for each analysis of the effect of four-wheel ABS in LTVs, the separate and composite effectiveness estimates, the significance-test results and the confidence bounds. Here is how the statistics are derived for the basic estimate of the effect of four-wheel ABS, relative to no ABS at all, in all non-control-group crashes on all roads.

The 2x2 table of actual case counts for the entire database created in Section 2.3.1 is:

	LTVs with 8% 4-wheel 92% rear-wheel	LTVs with 96% 4-wheel 4% rear-wheel
Control group involvements	4,585	4,349
All non-control-group involvements	10,167	9,851

The observed effect is:

$$1 - [(9{,}851/4{,}349) / (10{,}187/4{,}585)] = 2.15\text{-percent increase}$$

Table 2-8: LTVs, Distribution of Fatal Crash Involvements With and Without Four-Wheel ABS, FARS 1995-2007

	Actual FARS Case Counts		Air-Bag-Weighted N		Fatal Crash Reduction (%)			t for H_0 Red. = 0	90% Confidence Bounds	
	LTVs w 8% 4-whl 92% rear	LTVs w 96% 4-whl 4% rear	LTVs w 8% 4-whl 92% rear	LTVs w 96% 4-whl 4% rear	96/4 vs. 8/92	Rear-whl vs. no ABS	4-wheel vs. no ABS		Low	Upr
Control group involvements	4,585	4,349	4,618	4,406						
ALL ROADS										
All non-control-group involvements	10,167	9,851	10,381	10,332	-4	4	-1	.30	-8	5
All crash involvements							-1		-6	4
Run-off-road crashes	4,320	4,384	4,456	4,659	-10	4	-6	1.27	-16	3
Side impacts w fixed objects	469	480	473	486	-8	8	none	.04	-25	20
First-event rollovers	1,493	1,655	1,493	1,655	-16	7	-10	1.40	-24	3
Other run-off-road crashes	2,358	2,249	2,490	2,518	-6	2	-5	.82	-16	6
Pedestrian/bicyclist/animal	1,313	1,253	1,314	1,256	none	15	**14**	**2.27**	**3**	**25**
Culpable involvements w other veh	3,372	3,182	3,439	3,351	-2	1	-1	.36	-9	6
WET, SNOWY, OR ICY ROADS										
All non-control-group involvements	2,444	2,375	2,488	2,467	-4	-1	-6	1.18	-16	3
All crash involvements							-6		-15	3
Run-off-road crashes	748	803	774	852	-15	7	-10	1.20	-27	5
Side impacts w fixed objects	122	139	122	140	-20	16	-4	.15	-60	33
First-event rollovers	209	237	209	237	-19	-8	**-31**	**2.11**	**-66**	**-4**
Other run-off-road crashes	417	427	443	476	-13	10	-3	.29	-26	16
Pedestrian/bicyclist/animal	154	165	154	166	-13	1	-14	.77	-57	17
Culpable involvements w other veh	613	582	623	607	-2	-4	-6	.87	-21	7

However, the calculation based on actual case counts understates the increase with four-wheel ABS because it does not adjust for the effect of air bags being introduced more or less simultaneously with four-wheel ABS. The 2x2 table of case counts weighted upwards for the effect of air bags is:

	LTVs with 8% 4-wheel 92% rear-wheel	LTVs with 96% 4-wheel 4% rear-wheel
Control group involvements	4,618	4,406
All non-control-group involvements	10,381	10,332

Weighting the cases increases each cell count in the contingency table, but the lower-right cell more so than the others (because it has the highest proportion of frontal crashes in LTVs with air bags). The observed effect is now:

$$1 – [(10{,}332/4{,}406) / (10{,}381/4{,}618)] = 4.31\text{-percent increase}$$

That estimate is rounded to -4 percent and shown in the fifth column of the “all non-control-group crashes” row of Table 2-8. But that is the effect of increasing the market share of four-wheel ABS from 7.7 percent to 96.3 percent. The effect of increasing all the way from 100% rear-wheel ABS to 100% four-wheel ABS would be higher:

$$\{1 – [(10{,}332/4{,}406) / (10{,}381/4{,}618)]\} / \{.963 – .077 \times [(10{,}332/4{,}406) / (10{,}381/4{,}618)]\}$$

$$= 4.89\text{-percent increase}$$

But that is the estimated effect of shifting from rear-wheel to four-wheel ABS. The effect of shifting from no ABS at all to rear-wheel ABS has already been estimated in Section 2.2.2 to be a 3.61 percent reduction of crash involvements. It is rounded to 4 and shown in the sixth column of Table 2-8. (The sixth column of Table 2-8 recapitulates the fourth column of Table 2-6, the principal point estimates for rear-wheel ABS relative to no ABS.) The net effect of shifting from no ABS to four-wheel ABS is the composite of the two stepwise effects:

$$1 – [(1 – .0361) \times (1 + .0489)] = 1.10\text{-percent increase}$$

It is rounded to -1 percent and shown in the seventh column of Table 2-8. It is the principal point estimate for the effect of four-wheel ABS relative to no ABS.

Significance testing of this effect and estimation of its 90% confidence bounds are based on a procedure partly identical and partly somewhat different from Section 2.1.5. What is identical is that FARS is split up into 10 systematic random subsamples based on the last two digits of ST_CASE – and that procedure is replicated 11 times. In fact, the same ST_CASE numbers used in Section 2.1.5 are re-used here.

For example, on the first of the 11 times that FARS was split into 10 subgroups, subgroup 1 happened to consist of cases with ST_CASE ending in 01, 05, 06, 21, 23, 27, 38, 61, 65, or 81. Using the FARS database created in Section 2.2.1, but limited to the cases with ST_CASE ending in 01, 05, 06, 21, 23, 27, 38, 61, 65, or 81, we estimate the effect $E_{0R,1,1}$ of shifting from no ABS at all to 100% rear-wheel ABS (where 0R means "from no ABS to rear-wheel ABS," 1 is subgroup 1, 1 is replication 1 of the procedure). Using the FARS database created in Section 2.3.1 and again limiting to the cases with ST_CASE ending in 01, 05, 06, 21, 23, 27, 38, 61, 65, or 81, we estimate the effect $E_{R4,1,1}$ of shifting from 100% rear-wheel ABS to 100% four-wheel ABS (where R4 means "from rear-wheel to four-wheel ABS"). The composite effect:

$$E_{04,1,1} = 1 - [(1 - E_{0R,1,1}) \times (1 - E_{R4,1,1})]$$

is the estimate of shifting from no ABS to 100% four-wheel ABS, based solely on the FARS cases with ST_CASE ending in 01, 05, 06, 21, 23, 27, 38, 61, 65, or 81. Similarly, $E_{04,i,j}$ is the composite estimate for the ith subgroup in the jth replication of the procedure.

The composite effectiveness estimates are transformed into log-odds ratios:

$$L_{04,i,j} = \log(1 - E_{04,i,j})$$

For a particular replication j, let $s_{04,j}$ be the standard deviation of the 10 estimates $L_{04,i,j}$ (where i ranges from 1 to 10) for the 10 mutually exclusive subgroups of ST_CASE endings. The standard deviation $S_{04,j}$ of the corresponding estimate of effectiveness expressed as a log-odds ratio in the full datasets (10 times as many cases) is $S_{04,j} = s_{04,j} / \sqrt{10}$. Let S_{04} be the median of the 11 estimates $S_{04,j}$ obtained in the 11 replications.

Specifically, in the analysis of the effect of four-wheel ABS on all non-control-group crash involvements, the point estimate was a 1.10-percent increase. Expressed as a log-odds ratio:

$$L = \log(1 + .0110) = .0109$$

$$S_{04} = .0365$$

$$t = |L| / S_{04} = .30$$

Because t is less than 1.833 (the 95th percentile of a t-distribution with 9 degrees of freedom[58]), the observed fatal-crash increase for four-wheel ABS is not statistically significant at the one-sided .05 level.

The 90 percent confidence bounds for the effect of increasing all the way from zero ABS to 100 percent ABS are:

$$1 - [1 - \exp(L \pm 1.833 \times S_{04})] = 1 - [1 - \exp(.0109 \pm 1.833 \times .0365)]$$

= from an 8-percent increase to a 5 percent reduction

[58] Because each s_j is calculated by computing the variance of 10 observations (log r for each of 10 subgroups), it is appropriate to use a t test with 9 df to test if log r is significantly different from zero. Caveat: the assumption that the fairly complex statistic L is t-distributed is more tenuous than the corresponding assumption in Section 2.1.5.

The eighth column of Table 2-8 shows the t value for the effectiveness estimate of four-wheel ABS. The two right columns show the lower and upper 90 percent confidence bounds for the effect of four-wheel ABS – i.e., the shift from no ABS at all to 100 percent four-wheel ABS.

Now let us discuss the point and interval estimates for all the crash types in Table 2-8. Positive estimates (reductions in fatal crashes, relative to the control group, with ABS) are shown in black, negative estimates in red. Statistically significant point estimates are printed bold, and they are shaded light-blue if positive, yellow if negative. Non-significant estimates are not printed bold, and have a negative lower confidence bound and a positive upper bound.

The effect of four-wheel ABS on <u>all crashes</u>, including the control-group crashes where we assume it has no effect, is derived from the preceding estimate. Table 2-6 showed that, without any ABS, there were 3,577 control-group involvements and 8,722 response group involvements. The point estimate for all response-group crashes is a 1.10-percent increase. The effect of four-wheel ABS on all crashes is:

$$[8{,}722 / (3{,}577 + 8{,}722)] \times 1.10 = 0.78\text{-percent increase}$$

Its 90 percent confidence bounds, similarly derived, are from -6 to +4 percent.

Run-off-road crashes increased overall by a non-significant 6 percent ($t = 1.27$). The initial 4 percent reduction associated with rear-wheel ABS was somewhat more than canceled after the shift from rear-wheel to four-wheel ABS, associated with a 10-percent increase. In fact all eight analyses for run-off-road crashes (the four on all roads and the four on wet, snowy, or icy roads) showed an increase for four-wheel relative to rear-wheel ABS. That is consistent with the results for passenger cars (Table 2-2), where all eight types of run-off-road were observed to increase with ABS. But for LTVs, seven of the eight increases are partly or wholly offset by an observed improvement for rear-wheel ABS, resulting in a zero or non-significant negative composite effect for four-wheel ABS relative to no ABS. Only for rollovers on wet, snowy, or icy roads, where the observed effect for rear-wheel ABS was also negative, does the composite effect amount to a statistically significant increase at the one-sided .05 level (but not at the two-sided .05 level, because $t = 2.11$ does not exceed 2.262, the 97.5^{th} percentile of t with 9 df).

Rear-wheel ABS significantly reduced collisions with pedestrians, bicyclists and animals. The shift from rear-wheel to four-wheel ABS has little or no additional effect. The composite effect is a statistically significant 14 percent reduction ($t = 2.27$). However, there is no reduction on wet, snowy, or icy roads. The observed effect on culpable involvements in collisions with other vehicles is negligible.

2.3.3 Drinking versus non-drinking drivers

As of April 2009, FARS has enough cases of LTVs with four-wheel ABS to compare its effect on run-off-road crashes for drinking and non-drinking drivers, as Harless and Hoffer did for passenger cars.[59] Our analysis is identical to the procedure for cars in Section 2.1.7, except that it compares LTVs with a high proportion of four-wheel ABS to LTVs with primarily <u>rear-wheel</u>

[59] Harless & Hoffer (2002).

ABS. When entirely separate analyses are performed for non-drinking and drinking drivers, including control groups drawn only from these drivers, the increase in run-off-road crashes is almost identical for the two groups (9% and 10%, respectively):

With Separate Control Groups	LTVs with 8% 4-wheel 92% rear-wheel	LTVs with 96% 4-wheel 4% rear-wheel	Reduction for 4-Wheel ABS (%)
	Non-Drinking Drivers		
Control group	3,344	3,185	
Run-off-road	1,734	1,799	- 9
	Drinking Drivers		
Control group	178	175	
Run-off-road	1,920	2,073	- 10

When the same control group is used for the non-drinking and drinking drivers, namely the weighted counts for all cases as shown in Table 2-8, the effects on run-off-road crashes are likewise about the same:

With Joint Control Group	LTVs with 8% 4-wheel 92% rear-wheel	LTVs with 96% 4-wheel 4% rear-wheel	Reduction for 4-Wheel ABS (%)
	Non-Drinking Drivers		
Control group (from Table 2-8)	4,618	4,406	
Run-off-road	1,734	1,799	- 9
	Drinking Drivers		
Control group (from Table 2-8)	4,618	4,406	
Run-off-road	1,920	2,073	- 13

These results confirm the findings of Section 2.1.7 that the long-term increase in run-off-road crashes is not just a drinking-driver problem.

CHAPTER 3

EFFECT OF ABS IN ALL CRASHES: ANALYSES OF 1995-2007 GES DATA

3.0 Summary

ABS reduces the overall crash-involvement rate by a statistically significant 6 percent in passenger cars (90% confidence bounds 4 to 8%) and by a statistically significant 8 percent in LTVs (90% confidence bounds 3 to 11%). These are substantial reductions, comparable, for example, to the overall effects of electronic stability control.[60] For specific crash types, the effects of ABS in nonfatal crashes are not unlike the effects found in fatal crashes in Chapter 2: an increase in run-off-road crashes but a reduction in collisions with other vehicles, especially on wet roads. However, among nonfatal crashes, collisions with other vehicles far outnumber run-off-road crashes; the benefit of ABS in the former greatly overshadows any added harm in the latter.

3.1 Analysis for passenger cars

3.1.1 GES calendar-year range

The General Estimates System of the National Automotive Sampling System is a probability sample of police-reported crash involvements in the United States[61], drawn from 60 primary sampling units that are counties or groups of counties. When GES cases are weighted by the inverse sampling fractions, the weighted counts may ideally be used to generate unbiased estimates of national rates. "Ideally" – if there is no issue of missing data. However, information on the vehicle's make and model is completely missing in 15 percent of the weighted cases, mostly concentrated in seven of the 60 PSUs. But 85 percent of the data and 53 of 60 PSUs is still an acceptably "national" sample. On the other hand, limiting the data to vehicle cases with valid VINs and deriving the make and model from the VIN – the customary procedure in NHTSA evaluations – would have resulted in an excessive data loss of 28 percent of the cases, concentrated in 16 of the 60 PSUs. For the GES analyses, we will derive the make and model from the VIN if it is available; if not, we will accept the make and model specified on GES (which is usually quite accurate because it is derived from the State's own VIN decode programs).

As of April 2009, the GES database is complete through calendar year 2007. Only calendar years 1995-2007 are included in the analyses here, exactly as in the FARS analyses of Chapter 2. The goal is to study the "long-term" effect of ABS and not its "initial" effects. Calendar year 1995 has been selected as the starting point for the data because it was also the starting point in Hertz's 2000 report, the first to indicate that the initially deleterious effect of ABS on run-off-

[60] Dang (2007), p. viii; the estimated overall reductions in police-reported crash involvements are 8 percent in passenger cars and 10 percent in LTVs, respectively.
[61] The sample frame is the 48 contiguous States plus the District of Columbia.

road crashes had become non-significant, and because consumer information on the correct use of ABS began to appear in 1995.[62]

The basic analysis approach is identical to the FARS analyses of Chapter 2: count the number of crash involvements of various types that might conceivably be influenced by ABS and compute their ratios to the number of control group involvements that are unlikely to be affected by ABS. The ratios are compared for cars with ABS and cars of the same makes and models without ABS – in the same calendar years.

3.1.2 Control-group involvements versus response group

The control group and the response group are essentially identical to those in Chapter 2 – with the FARS definitions translated to their equivalents in GES – and similar to the ones in NHTSA's evaluation of electronic stability control.[63] The control group consists of cars that had been stopped or parked before they were hit by another vehicle; moving less than 10 mph, backing up, parking, or leaving a parking space; struck in the rear while moving; or involved as non-culpable parties in collisions with other vehicles on dry surfaces. The GES codes for control group crashes include the following involvements in collisions with other vehicles (VEH_INVL ≥ 2):

- Hit while stopped/parked: P_CRASH1 = 5, 7 or SPEED = 0
- Backing/parking/low-speed: P_CRASH1 = 4, 8, 9, 13 or SPEED = 1-10
- Struck in rear: IMPACT = 4, 13, 14
- Non-culpable involvements on dry roads: SUR_COND = 1; the following four variables do not have values that suggests this driver was culpable:
    - The "driver distraction" variable DR_DSTRD does not have values 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 97, or 98
    - The "contributing factor" variable FACTOR does not have values 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 97, or 98
    - The "critical event" variable P_CRASH2 does not have values 1, 3, 6, 8, 9, 10, or 11
    - The "violation" variable VIOLATN does not have values 1, 2, 3, 4, 5, 6, 7, 50, 97, or 98

All crash involvements that are not in the control group are in the response group. On roads that are not dry, even non-culpable involvements can be in the response group, because ABS is likely to benefit drivers in many situations and we do not want to "miss" a possible benefit just because GES classified a driver as non-culpable. In other words, on roads that are not dry, the control group is limited to the first three of the four categories listed above. Effectiveness of ABS (percent crash reduction relative to the control group) is computed for the response group as a whole, and also for the following subgroups – on all roads, and on roads that are not dry:

[62] Hertz (2000).
[63] Dang (2007).

- Run-off-road crashes: VEH_INVL = 1, but excluding EVENT1 = 2, 3, 8, 9, 10, 21, 22, 23, 24, 26, or 27 (collisions with non-motorists, trains, or parked cars, plus various non-collisions that usually happen on, not off the road)
  - First-event rollovers: EVENT1 = 1 or (EVENT1 = 38 or 39 and V_EVENT=1)
  - Side impacts with fixed objects: IMPACT = 2, 3, 13, or 14
  - All other run-off-road crashes
- Collisions with pedestrians, bicyclists, other non-motorists, or animals: VEH_INVL = 1 and EVENT1 = 21, 22, 24, or 27. Unlike FARS, where these are a substantial proportion of the fatal crashes and mostly involve pedestrians or bicyclists, in GES they are a small proportion of the nonfatal crashes and mostly involve animals. Effectiveness estimates will generally not be statistically meaningful and are computed mostly for comparison with the FARS results.
- Culpable involvements in collisions with other vehicles, including <u>any</u> frontal impact into the rear of another vehicle:
  - DR_DSTRD = 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 97, or 98, or
  - FACTOR = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 97, or 98, or
  - P_CRASH2 = 1, 3, 6, 8, 9, 10, or 11, or
  - VIOLATN = 1, 2, 3, 4, 5, 6, 7, 50, 97, or 98, or
  - MAN_COL = 1 and IMPACT = 1, 11, or 12 (front-to-rear impact)

3.1.3 Cars without ABS versus cars with ABS

The selection of vehicle is the same as in the FARS analyses, as described in Section 3.1.2 and it includes the 60 makes and models listed in Table 2-1 for the same ranges of model years. For each make and model, two model years without ABS or with a low percentage of optional ABS are compared to two other model years with standard ABS or a high percentage of optional ABS. For most models, the shift is from low to high ABS, but for some (shown in red on Table 2-1) the shift is from high to low. These four model years should be consecutive, or with at most a one-year gap between the first two and the last two. The analyses include an adjustment factor, if necessary, to translate the observed effect of changing from a low percentage to a high percentage of ABS to the effectiveness of changing from 0 to 100 percent ABS. As in Section 3.1.2, the calendar years included for each model range from 1995 or from the last of the four model years included for that model (whichever is later) through 2007.

In the FARS analyses, all vehicles were identified by decoding the VIN. With GES, we will also consider vehicle records with a make and model coded but no VIN. That works for most of the entries in Table 2-1, because all of the vehicles with a specific make and model code are selected for the same model years. But for some entries in Table 2-1 vehicles with the same code may be selected for different model years, depending on the sub-series. For example, Cadillac DeVille, Fleetwood FWD, and Fleetwood Brougham all have MAKE = 19 and MODEL = 3 but are selected for different model years. It takes the VIN to identify which is which. For these models, the GES analysis is limited to cases with valid VINs.

For the 60 makes and models combined, 6.8 percent of the cars in the low-ABS model-year range were equipped with ABS; 88.2 percent of the cars in the high-ABS model years had ABS. That is an 81.4 percentage-point gain in the share of cars equipped with ABS.

The analysis file includes 62,998 GES cases of cars involved in crashes. In raw numbers, that is substantially more than the 38,251 FARS cases available for the analyses of Section 2.1. But GES is not a simple random sample of crashes. It is a cluster sample and its design effect will reduce the statistical power of the analyses to the equivalent of simple random sample that is not nearly as large.

Unlike the FARS analyses, no adjustment or weighting of the data is needed to account for the fact that air bags were often introduced at more or less the same time as ABS. Air bags are not a crash-avoidance technology. When cars receive air bags, their probability of getting into a crash and onto GES is not diminished, even if the air bags might reduce some of the occupants' injuries in that crash.

3.1.4 Results

Table 3-1 shows the actual and weighted case counts for each analysis of the effect of ABS in passenger cars, the effectiveness estimates, the significance-test results and the confidence bounds. Here is how the statistics are derived for the basic estimate of the effect of ABS in all non-control-group crashes on all roads. The 2x2 contingency table of actual case counts for the entire database is:

	Cars with 7% ABS	Cars with 88% ABS
Control group involvements	14,478	16,489
All non-control-group involvements	15,613	16,418

Whereas the preceding table is of some value for indicating how many actual cases are included in the analysis, no meaningful effectiveness estimate can be derived from the cell counts. GES is a stratified cluster sample. For any kind of unbiased national estimate, each case needs to be weighted by the inverse of its national probability of selection.

Table 3-1: Passenger Cars, Distribution of Crash Involvements With and Without 4-Wheel ABS, GES 1995-2007

	Actual GES Case Counts		Weighted N		Crash Reduction (%)		t for H_0: Red. = 0	90% Confidence Bounds	
	Cars w 7% ABS	Cars w 88% ABS	Cars w 7% ABS	Cars w 88% ABS	88% vs. 7% ABS	100% vs. no ABS		Lower	Upper
Control group involvements	14,478	16,489	1,802,565	2,114,616					
ALL ROADS									
All non-control-group involvements	15,613	16,418	1,789,041	1,878,852	10	**13**	**4.99**	**8**	**17**
All crash involvements						**6**		**4**	**8**
Run-off-road crashes	3,125	3,725	319,209	376,924	-1	-1	.17	-10	8
Side impacts w fixed objects	630	847	70,029	95,275	-16	**-20**	**2.14**	**-40**	**-3**
First-event rollovers	370	453	31,969	36,642	2	3	.22	-23	23
Other run-off-road crashes	2,125	2,425	217,212	245,007	4	5	.91	-5	14
Pedestrian/bicyclist/animal	1,218	1,393	114,830	142,900	- 6	- 8	.71	-30	11
Culpable involvements w other veh	8,896	8,961	1,062,451	1,069,673	14	**17**	**6.39**	**13**	**22**
WET, SNOWY, OR ICY ROADS									
All non-control-group involvements	5,046	4,985	607,089	587,453	17	**21**	**5.76**	**15**	**27**
All crash involvements						**16**		**11**	**21**
Run-off-road crashes	918	1,227	107,858	140,209	-11	-13	1.59	-31	2
Side impacts w fixed objects	228	341	26,935	42,247	-34	**-43**	**2.81**	**-80**	**-13**
First-event rollovers	87	130	8,642	11,117	-10	-12	.57	-61	22
Other run-off-road crashes	603	756	72,281	86,845	-2	-3	.33	-21	13
Pedestrian/bicyclist/animal	166	175	16,796	21,048	- 7	- 8	.27	-86	37
Culpable involvements w other veh	1,946	1,657	241,359	195,464	31	**37**	**6.82**	**29**	**45**

The contingency table of weighted case counts is:

	Cars with 7% ABS	Cars with 88% ABS
Control group involvements	1,802,565	2,114,616
All non-control-group involvements	1,789,041	1,878,852

The observed effect of ABS is a substantial reduction of crash involvements:

$$1 - [(1{,}878{,}852/2{,}114{,}616) / (1{,}789{,}041/1{,}802{,}565)] = 10.48 \text{ percent reduction}$$

That estimate is rounded to 10 percent and shown in the fifth column of the "all non-control-group crashes" row of Table 3-1. But that is the effect of increasing the market share of ABS from 6.8 percent to 88.2 percent. The effect of increasing all the way from zero ABS to 100 percent ABS would be even higher:

$$\{1 - [(1{,}878{,}852/2{,}114{,}616) / (1{,}789{,}041/1{,}802{,}565)]\} / \{.882 - .068 \times [(1{,}878{,}852/2{,}114{,}616) / (1{,}789{,}041/1{,}802{,}565)]\}$$

$$= 12.77 \text{ percent reduction}$$

That estimate rounds to 13 percent and it is shown in the sixth column of Table 3-1, the column headed by "100% versus no ABS." It is the basic point estimate of the effect of ABS.

Statistical significance of the crash-involvement reductions cannot be tested with simple 2x2 chi-squares of the cell counts, because they are weighted counts from a stratified cluster sample, not actual numbers of cases from a simple random sample. The procedures for testing significance and estimating confidence bounds largely parallel the FARS procedures in Section 2.1.5, except that they take into account that GES, unlike FARS, is a cluster sample of 60 PSUs. The 60 PSUs are randomly split up into 10 subgroups of PSUs of approximately equal size – i.e., each subgroup containing close to 10 percent of the weighted cases of vehicles with known VIN and/or known codes for make and model. Thanks to the ample data available, effectiveness can be calculated separately in each subsample – i.e., each subgroup of PSUs – and significance tested by observing the variation of the estimate across the 10 subsamples.

However, the variance estimate obtained by running through the procedure just once could be too high or too low by chance, depending on what PSUs happened to get into the 10 subsamples. A second iteration of the same procedure, but with the GES PSUs split up into subgroups in a different way, might generate a lower or higher estimate. Numerous iterations, each with a different splitting of the GES PSUs into subgroups, will generate a range of variance estimates, and the median of these estimates will be used.

Specifically, each PSU has a two-digit identification number that is the value of the numeric variable PSU on the GES SAS file. The PSU identification numbers were randomly re-ordered by a SAS random-number generator and listed in the new order. The number of weighted vehicle cases (all vehicle types, all crash types – but with known VIN and/or make and model) during 1995-2007 was ascertained for each PSU and cumulated down the list. The list was parsed into consecutive (by the new PSU-ordering) groups of PSUs, each containing about 10 percent of the cases, and these subgroups of PSUs were numbered 0 to 9. The GES cases from the PSUs in the first subgroup on the new list became subsample 1, the cases from the PSUs in the second subgroup became subsample 2, and so on. After these 10 subsamples were created, the 60 PSUs were randomly reordered anew and another set of 10 subsamples was created. In all, the procedure was repeated 11 times and it created 11 sets of 10 subsamples each.

It is easier to work with the effect of increasing the market share of ABS from 6.8 percent to 88.2 percent than with the effect of increasing all the way from zero ABS to 100 percent ABS. The former can be expressed as a log-odds-ratio, which tends to have a normal distribution. If the former effect is significant, the latter will be, too.

Based on the weighted cell counts, the effect of increasing the market share of ABS from 6.8 percent to 88.2, estimated for the entire GES database, may be expressed as a log-odds ratio:

$$\log r = \log [(1{,}878{,}852/2{,}114{,}616) / (1{,}789{,}041/1{,}802{,}565)] = -.1107$$

On the first of the 11 times that the GES PSUs were split into 10 subgroups, subgroup 1 happened to consist of PSUs nos. 7, 21, 24, 25, 41, 43, 75, 77, and 79. For these cases, the corresponding log-odds ratio is:

$$\log r = \log [(157{,}959/156{,}500) / (245{,}115/212{,}741)] = -.1324$$

For subgroup 2, on the other hand, log r = -.1066; for subgroup 3, log r = -.1221; and so on. The standard deviation of 10 estimates for the 10 mutually exclusive subgroups of PSUs, each containing approximately a tenth of the GES data is .0425. The standard deviation S_1 of the corresponding estimate of log r in the full dataset (10 times as many cases) is $.0425 / \sqrt{10} = .0134$. This is the estimated standard deviation of log r, for the full dataset, based on our first run-through of splitting the GES into 10 subgroups.

On the second iteration, the estimate of the standard deviation S_2, derived from the 10 subsamples created on that iteration, was slightly higher, .0180. On the third iteration, $S_3 = .0196$. Over all 11 iterations, the estimates S_j ranged from .0120 to .0275. However, the median of these 11 estimates is S = .0222, which was the value obtained on the fifth iteration.[64]

For the full dataset, log r was -.1107. Because $t = |\log r| / S = .1107 / .0222 = 4.99$ is more than 1.833 (the 95^{th} percentile of a t-distribution with 9 degrees of freedom[65]), the observed crash reduction for ABS is statistically significant at the one-sided .05 level. In fact, because 4.99 is more than 3.250 (the 99.5^{th} percentile of a t-distribution with 9 degrees of freedom), the observed crash reduction for ABS is statistically significant at the two-sided .01 level.

The 90 percent confidence bounds for the effect of increasing all the way from zero ABS to 100 percent ABS are:

[64] Even though we have 62,998 GES cases but only 38,251 FARS cases available for analyses, S is higher for the GES analysis (.0222) than for the FARS analysis (.0198). That reflects the design effect due to cluster sampling.
[65] Because each s_j is calculated by computing the variance of 10 observations (log r for each of 10 subgroups), it is appropriate to use a t test with 9 df to test if log r is significantly different from zero.

$$\{1 - [1 - \exp(\log r \pm 1.833 \times S)]\} / \{.882 - .068 \times [1 - \exp(\log r \pm 1.833 \times S)]\}$$

$$= \{1 - [1 - \exp(-.1107 \pm 1.833 \times .0222)]\} / \{.882 - .068 \times [1 - \exp(-.1107 \pm 1.833 \times .0222)]\}$$

$$= \text{from an 8 percent to a 17 percent reduction}$$

The seventh column of Table 3-1 shows the t value for the effectiveness estimate of ABS. The two right columns show the lower and upper 90 percent confidence bounds for the effect of ABS – i.e., the shift from no ABS to 100% ABS.

Now let us discuss the point and interval estimates for all the crash types in Table 3-1. Positive estimates (reductions in crash involvements with ABS, relative to the control group) are shown in black, negative estimates in red. Statistically significant point estimates are printed bold, and they are shaded light-blue if positive, yellow if negative. Non-significant estimates are not printed bold, and have a negative lower confidence bound and a positive upper bound.

The effect of ABS on all crashes, including the control-group crashes where we assume it has no effect, is derived from the preceding estimate. Without ABS, there were 1,802,565 weighted control-group involvements and 1,789,041 response-group involvements. The point estimate for all response-group crashes is a 12.77 percent reduction. The point estimate for all crashes is:

$$[1{,}789{,}041 / (1{,}802{,}565 + 1{,}789{,}041)] \times 12.77 = 6.36 \text{ percent reduction}$$

Its 90 percent confidence bounds, similarly derived, are from 4 to 8 percent. That is indeed a substantial reduction of nonfatal crash involvements. For example, the corresponding estimate for electronic stability control is an 8-percent reduction.[66]

But ABS is not beneficial in every type of crash. Side impacts with fixed objects increase by a statistically significant 20 percent on all roads (t = 2.14) and by a statistically significant 43 percent on wet, snowy, or icy roads (t = 2.81). The two other types of run-off-road crashes show a non-significant reduction on all roads and a non-significant increase on wet, snowy, or icy roads. All run-off-road crashes are observed to increase by a non-significant 1 percent on all roads and a non-significant 13 percent on wet, snowy, or icy roads. In general, these results parallel the findings for fatal run-off-road crashes. But they are less important here, because run-off-road crashes are a smaller slice of the pie.

Collisions with pedestrians, bicyclists, or animals (which at the nonfatal level are mostly collisions with animals and proportionately few in number) showed non-significant increases. The point estimates are not statistically meaningful, but they provide no corroboration for the significant reduction seen at the fatal level.

The great benefit for ABS is prevention of culpable involvements with other vehicles. On all roads, the reduction is a statistically significant 17 percent (t = 6.39; confidence bounds, 13 to 22%). On wet, snowy, or icy roads, where ABS is much more likely to activate, the reduction is a remarkable 37 percent (t = 6.82; confidence bounds, 29 to 45%). Here, ABS does exactly what it was designed for: enabling drivers to stop in time and under control, avoiding vehicles that

[66] Dang (2007), p. viii.

encroach into their lane while not skidding into the paths of vehicles in other lanes. The results parallel the FARS analysis (a significant reduction on wet, snowy, or icy roads), except that they are substantially larger in magnitude and multi-vehicle crashes are a substantially larger slice of the pie. The reduction of multi-vehicle involvements far outweighs any increase in run-off-road crashes and produces a substantial net overall benefit, including a significant 21 percent reduction of all non-control group involvements on wet, snowy, or icy roads ($t = 5.76$; confidence bounds, 15 to 27%) and a 16 percent reduction of all involvements on these roads (confidence bounds, 11 to 21%).[67]

3.1.5 Comparative results for four cohorts of cars

Table 3-2 shows quite similar overall effects for ABS in four mutually exclusive cohorts of cars: (1) GM models that had a high percentage of ABS by 1993, (2) non-GM models that had a high percentage of ABS by 1993, (3) models that received a high share of ABS after 1993, and (4) models that dropped standard ABS, or where optional ABS lost substantial market share.

TABLE 3-2

OBSERVED EFFECT OF ABS BY CAR COHORT
(Weighted GES data, 1995-2007)

	Cars with Low % ABS	Cars with High % ABS	Reduction for ABS (%)
	GM models with ABS by 1993		
Control group involvements	790,498	891,325	
Non-control-group	846,501	856,681	10
	Non-GM models with ABS by 1993		
Control group involvements	193,920	273,208	
Non-control-group	190,372	226,770	15
	Models receiving ABS after 1993		
Control group involvements	665,345	750,496	
Non-control-group	587,444	602,495	9
	Models dropping ABS		
Control group involvements	152,802	199,587	
Non-control-group	164,725	192,907	10

[67] Without ABS, there were 189,984 weighted control-group involvements and 607,089 response-group involvements on wet, snowy, or icy roads.

Response-group crashes decreased in the first three cohorts after the cars received ABS, by 10 percent, 15 percent, and 9 percent, respectively. Response-group crashes increased in the fourth cohort by 10 percent after the cars dropped ABS. The observed overall effect of ABS is robust and does not appear to vary greatly depending on the specific ABS technology in the vehicles or the specific makes and models involved.

3.1.6 Net effect by specific road-surface condition

Table 3-3 compares the net effects of ABS on dry, wet, snowy, and icy roads. The observed net effect is 10 percent on dry roads and 19 percent on wet roads. There are not enough cases for statistically precise results on snowy or icy roads, but the observed reductions are similar to those on dry and wet roads.

TABLE 3-3

NET EFFECT OF ABS, BY ROAD-SURFACE CONDITION

	Weighted N of Crash Involvements		
	Cars w 7% ABS	Cars w 88% ABS	Reduction for ABS (%)
Control group involvements	1,802,565	2,114,616	
All non-control-group involvements on:			
Dry roads	1,158,091	1,261,393	10
Wet roads	472,769	448,776	19
Snowy or slushy roads	70,683	70,265	15
Icy roads	63,638	68,412	8

3.1.7 Net effect on injury crashes

Approximately one-third of the crashes on GES injured at least one of the people involved in the crash (occupants of any of the vehicles or non-motorists). When the basic analysis is limited to vehicles involved in crashes that injured somebody (possibly but not necessarily an occupant of that vehicle), the observed reduction in response-group involvements is 11 percent:

	Cars w 7% ABS	Cars w 88% ABS	Reduction for ABS (%)
Control group involvements	613,540	688,295	
All non-control-group involvements	613,925	613,269	11

That is nearly identical to the 10 percent reduction observed in all GES crashes (fifth column of Table 3-1). It demonstrates ABS is effective in preventing nonfatal-injury crashes (as opposed to fatal crashes), and that the reduction is about the same as for all crashes.

3.2 Analysis of rear-wheel ABS for LTVs

Almost all domestic pickup trucks, most domestic SUVs, and many vans and foreign-based-nameplate LTVs received ABS for the rear wheels only in the late 1980s or early 1990s. Four-wheel ABS usually did not arrive on LTVs until at least several model years later. The analysis of rear-wheel ABS for LTVs closely parallels the procedures described in Section 3.1. It, too, is based on GES data for calendar years 1995 to 2007. The control group and response group of crash involvements are defined exactly as in Section 3.1.2. The control group consists of LTVs that were stopped, parked, backing, moving slower than 10 mph, parking, leaving a parking place, were struck in the rear, or were non-culpable parties to a collision involving two or more vehicles.

The 31 makes and models included in the analysis and the range of model years for each model are listed in Table 2-5 of the preceding chapter. In the FARS analyses, all vehicles were identified by decoding the VIN. With GES, we will also consider vehicle records with a make and model coded but no VIN. That works for almost every model in Table 2-5, because all of the vehicles with a specific make and model code are selected for the same model years. But for the last model in Table 2-5, the Suzuki Sidekick, where the analysis is limited to the VIN-identifiable two-door sub-series, the GES analysis is limited to cases with valid VINs.

All models in Table 2-5 except the Nissan pickup have model-year ranges that end before 1995 and all GES cases from CY 1995 to 2007 will be included for those models. For the Nissan pickup, the model year range extends to 1996; only GES data from 1996 to 2007 will be included. For the 31 makes and models combined, 1.2 percent of the LTVs in the low-ABS model-year range were equipped with ABS; 100 percent of the LTVs in the high-ABS model years had rear-wheel ABS. That is a 98.8 percentage-point gain in the share of LTVs equipped with rear-wheel ABS.

The analysis file includes 29,030 GES cases of LTVs involved in crashes. That is slightly more than the 26,324 FARS cases available for the analyses of Section 2.2. But GES being a cluster sample will reduce the statistical power of the analyses as compared to the FARS results.

3.2.1 Results

Table 3-4 shows the actual case counts for each analysis of the effect of rear-wheel ABS in LTVs, the effectiveness estimates, the significance-test results and the confidence bounds. Here is how the statistics are derived for the basic estimate of the effect of ABS in all non-control-group crashes on all roads.

Table 3-4: LTVs, Distribution of Crash Involvements With and Without Rear-Wheel ABS, GES 1995-2007

	Actual GES Case Counts		Weighted N		Crash Reduction (%)		t for H_0: Red. = 0	90% Confidence Bounds	
	LTVs w 1% ABS	LTVs w 100% ABS	LTVs w 1% ABS	LTVs w 100% ABS	100% vs. 1% ABS	100% vs. no ABS		Lower	Upper
Control group involvements	6,260	7,465	813,267	940,476					
ALL ROADS									
All non-control-group involvements	6,971	8,334	847,914	1,006,270	1	1	.20	-5	5
All crash involvements						none		-2	3
Run-off-road crashes	1,825	2,046	189,089	206,140	9	9	1.67	-1	17
Side impacts w fixed objects	336	368	41,439	42,133	15	15	1.35	-6	32
First-event rollovers	425	416	37,383	37,253	16	17	1.76	-1	31
Other run-off-road crashes	1,065	1,262	110,267	126,753	4	4	.58	-9	15
Pedestrian/bicyclist/animal	493	616	48,448	67,617	-17	-17	1.47	-43	4
Culpable involvements w other veh	3,612	4,384	459,707	551,680	-1	-1	.18	-7	5
WET, SNOWY, OR ICY ROADS									
All non-control-group involvements	2,298	2,727	296,705	350,198	1	1	.28	-6	8
All crash involvements						1		-5	6
Run-off-road crashes	590	641	69,812	74,109	11	11	1.11	-8	27
Side impacts w fixed objects	144	156	19,373	19,694	15	15	1.01	-14	37
First-event rollovers	112	116	10,454	11,597	7	7	.39	-31	34
Other run-off-road crashes	334	369	39,885	42,818	10	10	.87	-13	29
Pedestrian/bicyclist/animal	67	59	8,233	7,974	19	19	.63	-50	56
Culpable involvements w other veh	844	985	111,512	132,713	none	none	.04	-12	11

The 2x2 contingency table of actual case counts for the entire database is:

	LTVs with 1% ABS	LTVs with 100% ABS
Control group involvements	6,260	7,465
All non-control-group involvements	6,971	8,334

Whereas the preceding table is of some value for indicating how many actual cases are included in the analysis, no meaningful effectiveness estimate can be derived from the cell counts. GES is a stratified cluster sample. For any kind of unbiased national estimate, each case needs to be weighted by the inverse of its national probability of selection.

The contingency table of weighted case counts is:

	LTVs with 1% ABS	LTVs with 100% ABS
Control group involvements	813,267	940,476
All non-control-group involvements	847,914	1,006,270

The observed effect of ABS is a negligible reduction of crash involvements:

$$1 - [(1{,}006{,}270/940{,}476) / (847{,}914/813{,}267)] = 0.55 \text{ percent reduction}$$

That estimate is rounded to 1 percent and shown in the fifth column of the "all non-control-group crashes" row of Table 3-4. But that is the effect of increasing the market share of rear-wheel ABS from 1.2 percent to 100 percent. The effect of increasing all the way from zero ABS to 100 percent ABS would be marginally higher:

$$\{1 - [(1{,}006{,}270/940{,}476) / (847{,}914/813{,}267)]\} / \{1 - .012 \times [(1{,}006{,}270/940{,}476) / (847{,}914/813{,}267)]\}$$

$$= 0.56 \text{ percent reduction}$$

That estimate again rounds to 1 percent and it is shown in the sixth column of Table 3-4, the column headed by "100% versus no ABS." It is the basic point estimate of the effect of rear-wheel ABS.

The t-tests for statistical significance of the point estimates and the estimation of 90 percent confidence bounds are based on the same procedure as for passenger cars (Section 3.1.4). The t value for the preceding point estimate is .20. Because that is less than 1.833 (the 95th percentile of a t-distribution with 9 degrees of freedom[68]), the observed crash reduction for rear-wheel ABS is not statistically significant at the one-sided .05 level. The 90 percent confidence bounds for

[68] See Section 3.1.4.

effectiveness range from a 5-percent increase to a 5 percent reduction in crash involvements. The t values and confidence bounds are shown in the last three columns of Table 3-4.

Now let us discuss the point and interval estimates for all the crash types in Table 3-4. Positive estimates (reductions in fatal crashes with ABS, relative to the control group) are shown in black, negative estimates in red. None of the point estimates is statistically significant; if any had been, they would have been printed bold and shaded light-blue if positive, yellow if negative.

The observed effect of rear-wheel ABS on <u>all crashes</u>, including the control-group crashes where we assume it has no effect, is:

[847,914 / (813,267 + 847,914)] x 0.56 = 0.28 percent reduction (rounded to zero%)

Its 90 percent confidence bounds, similarly derived, are from -2 to +3 percent.

Each of the eight observed effects on run-off-road crashes is positive: overall, and for each of the three subgroups of run-off-road crashes; on all roads as well as on wet, snowy, or icy roads. Observed reductions range from 4 to 16 percent. But none are statistically significant. The findings are consistent with the mildly positive results in the FARS analysis.

Results for collisions with animals and non-motorists conflict: a 17-percent increase on all roads but a 19 percent reduction on wet, snowy, or icy roads. Based on small numbers of cases, the estimates are not statistically meaningful. The observed effects on culpable involvements with other vehicles are close to zero.

3.3 Analysis of four-wheel ABS for LTVs

Most makes and models of LTVs that were eventually equipped with four-wheel ABS first went through an intermediate stage of only rear-wheel ABS, typically for at least several years. As in Section 2.3, the effect of four-wheel ABS is estimated in two essentially separate steps: as the composite of the effect of switching from no ABS to rear-wheel ABS (already estimated in Section 3.2) and the effect of switching from rear-wheel to four-wheel ABS.

The analysis of switching from rear-wheel to four-wheel ABS for LTVs closely parallels the ABS analysis for passenger cars (Section 3.1). It is based on GES data for calendar years 1995 to 2007. The control group and response group are defined the same way. Significance testing and estimation of confidence bounds parallels the FARS analysis (Section 2.3).

The 29 makes and models included in the analysis and the range of model years for each model are listed in Table 2-7 of the preceding chapter. In the FARS analyses, all vehicles were identified by decoding the VIN. With GES, we will also consider vehicle records with a make and model coded but no VIN. However, when two sub-series with the same model code are included for different model years (and the identification of the sub-series is based on the VIN), such as the Chevrolet Astro cargo van and wagon, the GES analysis is limited to cases with valid VINs.

For the models in Table 2-7 with model-year ranges that end before 1995, all GES cases from CY 1995 to 2007 are included. For the other models, GES data are included beginning only with the last model year in the range. For the 29 makes and models combined, 7.7 percent of the LTVs in the two earlier model years were equipped with four-wheel ABS (and 92.3 percent with rear-wheel ABS); 96.3 percent of the LTVs in the two later model years had four-wheel ABS (and 3.7 percent had rear-wheel ABS). That is an 88.6 percentage-point gain in the share of LTVs equipped with four-wheel ABS.

The analysis file includes 37,142 GES cases of LTVs involved in crashes. That is more than the 28,952 FARS cases available for the analyses of Section 2.3. But GES being a cluster sample will reduce the statistical power of the analyses as compared to the FARS results.

3.3.1 Results

Table 3-5 shows the actual and weighted case counts for each analysis of the effect of four-wheel ABS in LTVs, the separate and composite effectiveness estimates, the significance-test results and the confidence bounds. Here is how the statistics are derived for the basic estimate of the effect of four-wheel ABS, relative to no ABS at all, in all non-control-group crashes on all roads.

The 2x2 contingency table of actual case counts for the entire database is:

	LTVs with 8% 4-wheel 92% rear-wheel	LTVs with 96% 4-wheel 4% rear-wheel
Control group involvements	8,834	9,415
All non-control-group involvements	9,593	9,300

Whereas the preceding table is of some value for indicating how many actual cases are included in the analysis, no meaningful effectiveness estimate can be derived from the cell counts. GES is a stratified cluster sample. For any kind of unbiased national estimate, each case needs to be weighted by the inverse of its national probability of selection.

The contingency table of weighted case counts is:

	LTVs with 8% 4-wheel 92% rear-wheel	LTVs with 96% 4-wheel 4% rear-wheel
Control group involvements	1,107,216	1,198,921
All non-control-group involvements	1,124,731	1,061,334

Table 3-5: LTVs, Distribution of Crash Involvements With and Without Four-Wheel ABS, GES 1995-2007

	Actual GES Case Counts		Weighted N		Crash Reduction (%)			t for H_0 Red. = 0	90% Confidence Bounds	
	LTVs w 8% 4-whl 92% rear	LTVs w 96% 4-whl 4% rear	LTVs w 8% 4-whl 92% rear	LTVs w 96% 4-whl 4% rear	96/4. vs. 8/92	Rear-whl vs. no ABS	4-wheel vs. no ABS		Low	Upr
Control group involvements	8,834	9,415	1,107,216	1,198,921						
ALL ROADS										
All non-control-group involvements	9,593	9,300	1,124,731	1,061,334	13	1	**15**	**3.13**	**6**	**22**
All crash involvements							**8**		**3**	**11**
Run-off-road crashes	2,341	2,500	228,394	242,289	2	9	11	1.52	-2	22
Side impacts w fixed objects	363	488	41,006	55,178	-24	15	-9	.55	-45	18
First-event rollovers	554	641	45,711	49,325	none	17	17	1.45	-5	34
Other run-off-road crashes	1,424	1,371	141,677	137,786	10	4	15	1.60	-2	29
Pedestrian/bicyclist/animal	666	768	67,372	86,132	-18	-17	**-42**	**2.11**	**-91**	**-5**
Culpable involvements w other veh	5,275	4,838	657,972	579,524	19	-1	**20**	**4.32**	**12**	**28**
WET, SNOWY, OR ICY ROADS										
All non-control-group involvements	3,048	2,862	370,759	336,386	16	1	**19**	**3.10**	**8**	**28**
All crash involvements							**14**		**6**	**22**
Run-off-road crashes	818	973	92,893	108,351	-8	11	3	.23	-28	27
Side impacts w fixed objects	156	246	21,294	30,037	-30	15	-15	.66	-69	22
First-event rollovers	185	209	17,261	18,862	-1	7	6	.29	-40	37
Other run-off-road crashes	477	518	54,337	59,452	-1	10	9	.52	-28	36
Pedestrian/bicyclist/animal	73	98	7,563	10,736	-31	19	-10	.24	-134	48
Culpable involvements w other veh	1,136	861	149,478	108,492	33	none	**36**	**4.79**	**24**	**46**

The observed effect of increased installations of four-wheel ABS is:

$$1 - [(1{,}061{,}334/1{,}198{,}921) / (1{,}124{,}731/1{,}107{,}216)] = 12.85 \text{ percent reduction}$$

That estimate is rounded to 13 percent and shown in the fifth column of the "all non-control-group crashes" row of Table 3-5. But that is the effect of increasing the market share of four-wheel ABS from 7.7 percent to 96.3 percent. The effect of increasing all the way from 100 percent rear-wheel ABS to 100 percent four-wheel ABS would be even more beneficial:

$$\{1 - [(1{,}061{,}334/1{,}198{,}921) / (1{,}124{,}731/1{,}107{,}216)]\} / \{.963 - .077 \text{ x } [(1{,}061{,}334/1{,}198{,}921) / (1{,}124{,}731/1{,}107{,}216)]\}$$

$$= 14.35 \text{ percent reduction}$$

But that is the estimated effect of shifting from rear-wheel to four-wheel ABS. The effect of shifting from no ABS at all to rear-wheel ABS has already been estimated in Section 3.2.1 to be a negligible 0.56 percent reduction of crash involvements. It is rounded to 1 and shown in the sixth column of Table 3-5. (The sixth column of Table 3-5 recapitulates the sixth column of Table 3-4, the principal point estimates for rear-wheel ABS relative to no ABS.) The net effect of shifting from no ABS to four-wheel ABS is the composite of the two stepwise effects:

$$1 - [(1 - .0056) \text{ x } (1 - .1435)] = 14.83 \text{ percent reduction}$$

It is rounded to 15 percent and shown in the seventh column of Table 3-5. It is the principal point estimate for the effect of four-wheel ABS relative to no ABS.

Significance testing of this effect and estimation of its 90 percent confidence bounds combines the computational procedure used on FARS in Section 2.3.2 with the GES subsamples selected in the GES analysis for passenger cars (Section 3.1.4). In that analysis, the GES PSUs were randomly re-ordered. The list of the PSUs in the new order was split up into 10 subgroups of approximately equal size. That procedure was replicated 11 times. In fact, the same subgroups of PSUs used in Section 3.1.4 are re-used here.

For example, on the first of the 11 times that GES PSUs were split into 10 subgroups, subgroup 1 happened to consist of PSUs nos. 7, 21, 24, 25, 41, 43, 75, 77, and 79. Using the GES database created in Section 3.2., but limited to PSUs nos. 7, 21, 24, 25, 41, 43, 75, 77, and 79, we estimate the effect $E_{0R,1,1}$ of shifting from no ABS at all to 100 percent rear-wheel ABS (where 0R means "from no ABS to rear-wheel ABS," 1 is subgroup 1, 1 is replication 1 of the procedure). Using the current GES database and again limiting to PSUs nos. 7, 21, 24, 25, 41, 43, 75, 77, and 79, we estimate the effect $E_{R4,1,1}$ of shifting from 100 percent rear-wheel ABS to 100 percent four-wheel ABS (where R4 means "from rear-wheel to four-wheel ABS"). The composite effect is:

$$E_{04,1,1} = 1 - [(1 - E_{0R,1,1}) \text{ x } (1 - E_{R4,1,1})]$$

is the estimate of shifting from no ABS to 100 percent four-wheel ABS, based solely on the GES cases from PSUs nos. 7, 21, 24, 25, 41, 43, 75, 77, and 79. Similarly, $E_{04,i,j}$ is the composite estimate for the ith subgroup in the jth replication of the procedure.

The composite effectiveness estimates are transformed into log-odds ratios:

$$L_{04,i,j} = \log(1 - E_{04,i,j})$$

For a particular replication j, let $s_{04,j}$ be the standard deviation of the 10 estimates $L_{04,i,j}$ (where i ranges from 1 to 10) for the 10 mutually exclusive subgroups of PSUs. The standard deviation $S_{04,j}$ of the corresponding estimate of effectiveness expressed as a log-odds ratio in the full datasets (10 times as many cases) is $S_{04,j} = s_{04,j} / \sqrt{10}$. Let S_{04} be the median of the 11 estimates $S_{04,j}$ obtained in the 11 replications.

Specifically, in the analysis of the effect of four-wheel ABS on all non-control-group crash involvements, the point estimate was a 14.83 percent reduction. Expressed as a log-odds ratio:

$$L = \log(1 - .1483) = -.1605$$

$$S_{04} = .0512$$

$$t = |L| / S_{04} = 3.13$$

Because t is greater than 1.833 (the 95th percentile of a t-distribution with 9 degrees of freedom[69]), the observed crash reduction for four-wheel ABS is statistically significant at the one-sided .05 level. In fact, because t is greater than 2.821 (the 99th percentile of a t-distribution with 9 df), the observed crash reduction for four-wheel ABS is statistically significant at the one-sided .01 level.

The 90 percent confidence bounds for the effect of increasing all the way from zero ABS to 100 percent ABS are:

$$1 - [1 - \exp(L \pm 1.833 \times S_{04})] = 1 - [1 - \exp(-.1483 \pm 1.833 \times .0512)]$$

$$= \text{from a 6 percent to a 22 percent reduction}$$

The eighth column of Table 3-5 shows the t value for the effectiveness estimate of four-wheel ABS. The two right columns show the lower and upper 90 percent confidence bounds for the effect of four-wheel ABS – i.e., the shift from no ABS at all to 100 percent four-wheel ABS.

Now let us discuss the point and interval estimates for all the crash types in Table 3-5. Positive estimates (reductions in fatal crashes, relative to the control group, with ABS) are shown in black, negative estimates in red. Statistically significant point estimates are printed bold, and they are shaded light-blue if positive, yellow if negative. Non-significant estimates are not printed bold, and have a negative lower confidence bound and a positive upper bound.

The effect of four-wheel ABS on <u>all crashes</u>, including the control-group crashes where we assume it has no effect, is derived from the preceding estimate. Table 3-4 showed that, without any ABS, there were 813,267 control-group involvements and 847,914 response group involvements. The point estimate for all response-group crashes is a 14.83 percent reduction. The effect of four-wheel ABS on all crashes is:

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[69] Because each s_j is calculated by computing the variance of 10 observations (log r for each of 10 subgroups), it is appropriate to use a t test with 9 df to test if log r is significantly different from zero. Caveat: the assumption that the fairly complex statistic L is t-distributed is more tenuous than the corresponding assumption in Section 3.1.4.

$$[847{,}914 / (813{,}267 + 847{,}914)] \times 14.83 = 7.57 \text{ percent reduction}$$

Its 90 percent confidence bounds, similarly derived, are from 3 to 11 percent.

Run-off-road crashes decreased overall by a non-significant 11 percent ($t = 1.52$). The initial 9-percent reduction associated with rear-wheel ABS was augmented by an additional 2 percent reduction after the shift from rear-wheel to four-wheel ABS. A non-significant increase in side impacts with fixed objects was more than offset by reductions in rollovers and other run-off-road crashes. The results on wet, snowy, or icy roads are similar.

Collisions with animals or non-motorists increased by 42 percent, statistically significant at the one-sided but not the two-sided .05 level.[70] But on wet, snowy, or icy roads, the observed effect was only a non-significant 10-percent increase. It is not clear how statistically meaningful these findings are, but they provide no corroboration and perhaps even raise a question about the statistically significant reductions observed in fatal collisions with pedestrians, bicyclists, and animals.

The great benefit for ABS, for LTVs just as for passenger cars is prevention of culpable involvements with other vehicles. On all roads, the reduction is a statistically significant 20 percent ($t = 4.32$; confidence bounds, 12 to 28%). On wet, snowy, or icy roads, where ABS is much more likely to activate, the reduction is a remarkable 36 percent ($t = 4.79$; confidence bounds, 24 to 46%). Here, ABS evidently enables drivers to stop in time and under control, avoiding vehicles in their own lane while not invading other lanes. The overall reduction of non-control group involvements on wet, snowy, or icy roads is a significant 19 percent ($t = 3.10$; confidence bounds, 8 to 28%) and the reduction of all crashes on these roads is 14 percent (confidence bounds, 6 to 22%).

The five statistically significant reductions in Table 3-5, 15, 8, 20, 19, and 36 percent are almost identical to the corresponding significant crash reduction for passenger cars in Table 3-1: 13, 6, 17, 21, and 37 percent. This shows ABS effectiveness is consistent across the two types of passenger vehicles, cars and LTVs.

[70] $t = 2.11$; t must exceed 1.833 for significance at the one-sided .05 level and 2.262 for significance at the two-sided .05 level.

CHAPTER 4

DISCUSSION

4.1 Summary and comparison of effectiveness estimates

Table 4-1 summarizes the effectiveness estimates for four-wheel ABS – the findings of Chapters 2 and 3 – in fatal crashes and in all crashes; for passenger cars versus LTVs; on all roads and on wet, snowy, or icy roads; by type of crash.

TABLE 4-1: ESTIMATED CRASH REDUCTION (%) BY FOUR-WHEEL ABS, 1995-2007
[Reduction, Increase, **Significant Reduction** (one-sided p < .05), **Significant Increase**]

	All Roads		Wet, Snowy, or Icy Roads	
	Cars	**LTVs**	**Cars**	**LTVs**
FATAL CRASH INVOLVEMENTS				
All fatal involvements	1	- 1	- 1	- 6
All non-control-group involvements	1	- 1	- 1	- 6
All run-off-road crashes	**- 9**	- 6	**- 34**	- 10
Side impacts with fixed objects	**- 30**	none	**- 85**	- 4
First-event rollovers	- 11	- 10	**- 52**	**- 31**
All other run-off-road crashes	- 3	- 5	**- 17**	- 3
Pedestrian/bicyclist/animal	**13**	**14**	none	- 14
Culpable involvements w other veh	4	- 1	**12**	- 6
ALL CRASH INVOLVEMENTS				
All crash involvements	**6**	**8**	**16**	**14**
All non-control-group involvements	**13**	**15**	**21**	**19**
All run-off-road crashes	- 1	11	- 13	3
Side impacts with fixed objects	**- 20**	- 9	**- 43**	- 15
First-event rollovers	3	17	- 12	6
All other run-off-road crashes	5	15	- 3	9
Pedestrian/bicyclist/animal	- 8	**- 42**	- 8	- 10
Culpable involvements w other veh	**17**	**20**	**37**	**36**

Effects are largely consistent across vehicle types, severity levels, and roadway conditions.

- The overall effect of ABS on fatal crash involvements was close to zero in both cars (observed 1% reduction) and LTVs (observed 1% increase).
- The overall effect of ABS on nonfatal crash involvements was beneficial and statistically significant in both cars (observed 6% reduction) and LTVs (observed 8% reduction).
- The observed overall effect on run-off-road crashes is always negative for cars and negative at the fatal level for LTVs. It is negative and significant for car fatalities. It is consistently more negative on wet, snowy, or icy roads, where ABS is most likely to activate, than on all roads.
    - ABS has an observed negative effect on every subgroup of run-off-road crashes for passenger cars at the fatal level (all roads and wet-snowy-icy roads) and on wet, snowy, or icy roads at the nonfatal level.
    - On wet, snowy, or icy roads, every subgroup of fatal run-off-road crashes increased significantly for passenger cars. Every subgroup also increased for LTVs, but only one of them significantly (rollovers).
    - Run-off-road crashes on wet, snowy, or icy roads increased with ABS in each of four separate cohorts of cars: GM models that had received ABS by 1993, non-GM cars that had received ABS by 1993, models that received ABS after 1993, and models that dropped standard ABS (see Table 2-3).
    - The net effects on run-off-road crashes are less unfavorable in LTVs because the initial shift from no ABS to rear-wheel ABS was generally beneficial. But the subsequent shift from rear-wheel to four-wheel ABS usually increased run-off-road crashes in LTVs, including every type of fatal run-off-road crash and every type on wet, snowy, or icy roads (see Tables 2-8 and 3-5).
- The increase was always greater in side impacts with fixed objects than in other types of run-off-road crashes, except for LTV fatalities. All four observed effects for passenger cars on side impacts with fixed objects were negative and significant. Side impacts with fixed objects appear to epitomize the negative effect of ABS on run-off-road crashes.
    - Side impacts with fixed objects increased with ABS in each of the four separate cohorts of cars.
- Results were least consistent for collisions with pedestrians, bicyclists, and animals. The overall effect on fatal crashes was consistent between cars (significant 13% reduction) and LTVs (significant 14% reduction). But the observed effects on wet, snowy, or icy roads and on nonfatal crashes (mostly collisions with animals) were not positive.
- The effect on culpable involvements with other vehicles is consistently positive, except for LTVs at the fatal level. Five of the eight observed effects are a statistically significant benefit.
    - The effect on nonfatal culpable involvements with other vehicles is nearly identical for cars and LTVs; it is always significant and positive.

- The effect on nonfatal culpable involvements with other vehicles on wet, snowy or icy roads is a remarkable 37 percent reduction in cars and 36 percent in LTVs. Here is where ABS is the most effective.

4.2 Why is the effect still negative in run-off-road crashes?

It is unknown why run-off-road crashes are still increasing with ABS. But the 9-percent increase of fatal run-off-road crashes in passenger cars is statistically significant, and so is the 34-percent increase on wet, snowy and icy roads. Table 4-1 also shows four significant increases in side impacts with fixed objects and two significant increases in first-event rollovers.

It is important to note, however, that the increase is not nearly as large as in the early years of ABS. NHTSA's analysis of CY 1989 to 1993 FARS data and the Insurance Institute for Highway Safety's analysis of CY 1993 to 1995 FARS data each showed a 28-percent increase of fatal run-off-road crashes for passenger cars with ABS.[71] This study shows only a 9-percent increase in FARS data from 1995 to 2007; furthermore, the increase during 1995 to 2007 is similar in the older and more recent cohorts of cars – i.e., the age or design of the car does not appear to be the issue, since relatively new cars with the latest ABS technology are showing about the same increases as the older cars with first-generation ABS. That suggests the substantially higher increase before 1995 may be related to drivers' lack of understanding how to use ABS. The safety community's effort to inform the public about ABS and the simple passage of time and spread of the technology may have substantially attenuated but not eliminated the increase in run-off-road crashes. Maybe the effect is still negative simply because a portion of the public still doesn't know how to use ABS, or has had little experience in applying that knowledge because ABS is activated rather infrequently over the life of a vehicle.

At this time there is little or no empirical support for some of the other hypotheses. Research projects conducted after 1995, using a driving simulator or tracking the actual maneuvers of volunteer drivers on the road (see Section 1.5), found little evidence that drivers engaged in evasive maneuvers that, with ABS, resulted in running off the road. These projects likewise found little or no evidence that drivers became more aggressive because their vehicles are equipped with ABS. There have been occasional performance issues with some ABS systems on unusual road surfaces, but no link between these issues and fatal run-off-road crashes.

Side impacts with fixed objects have consistently increased more with ABS than other types of run-off-road crashes, especially on wet roads (85% fatality increase in cars). A distinctive feature of side impacts with fixed objects is that the vehicle was probably yawing rather than strictly rolling forward prior to impact.[72] ABS can prevent yawing associated with lockup of the rear wheels, but it will not necessarily prevent yawing due to steering input that results in the loss of tire adhesion. Whereas ABS theoretically preserves steering control while braking, the amount of permissible steering input may be quite limited on a wet road when much of the tire adhesion is already consumed by braking. Even moderate steering – well short of wild evasive maneuvers – may initiate a yaw (oversteering). An electronic stability control (ESC) system

[71] Kahane (1994), p. 95; Farmer et al (1996).
[72] This may not always be true, as impacts to the front of the vehicle near the corner may sometimes be reported as side impacts.

would take immediate, automatic action to counteract the yaw, but ABS alone, without ESC, usually cannot do so. The persistent increase in run-off-road crashes may to some extent reflect that ABS is an incomplete crash-avoidance technology; ESC makes it a more complete system.

4.3 Combined effect of four-wheel ABS and ESC

FMVSS No. 126 will require ESC in all new cars and LTVs after September 1, 2011. All ESC-equipped vehicles to date have also been equipped with four-wheel ABS. As explained in Section 1.7, that is unlikely to change in the future, because ESC essentially incorporates the functions and components of ABS. In model year 2005, just before SAFETEA-LU[73] triggered the ESC rulemaking process, approximately 40 percent of new cars and 10 percent of new LTVs were not yet equipped with ABS. In a sense, these models will be receiving a "package" of ABS and ESC.

What will be the combined effect of the technologies on crashes in general and on run-off-road crashes in particular? NHTSA's 2007 evaluation estimated crash reductions for ESC with ABS relative to vehicles with ABS alone, based on statistical analyses of crash data through CY 2004.[74] Table 4-2 shows the effect on fatal involvements of ABS alone, the incremental effect of ESC in a vehicle equipped with ABS, and the combined effect of ESC plus ABS relative to a vehicle equipped with neither. For example, if the observed effective of ABS on all fatal involvements of cars is a 1 percent reduction and the effect of ESC is a 14 percent reduction, the combined effect is a $1 - [(1 - .01) \times (1 - .14)] = 15$ percent reduction.

The combined effect is always a substantial fatality reduction. Even for run-off-road crashes, the negative effect of ABS is dwarfed by the benefit of ESC. According to Table 4-2, the combination of ABS and ESC will reduce fatal run-off-road crashes by an estimated 30 percent in passenger cars and by 68 percent in LTVs. One caveat on Table 4-2 is that these are early estimates of ESC effectiveness, based on the crash experience of the models equipped with ESC by 2004; NHTSA plans follow-up statistical analyses to estimate the long-term effectiveness of ESC, analogous to this report's numbers for ABS.[75]

[73] Public Law 109-59, August 10, 2005.
[74] Dang (2007), pp. vii and viii.
[75] Allen et al. (2008), p. 16.

TABLE 4-2

COMBINED EFFECT OF FOUR-WHEEL ABS AND ESC ON FATAL CRASHES

	Percent Reduction of Fatal Involvements		
	Four-Wheel ABS	ESC	Combined
Passenger cars			
All fatal involvements	1	14	15
All run-off-road crashes	– 9	36	30
Culpable involvements w other veh	4	19	22
LTVs			
All fatal involvements	– 1	28	27
All run-off-road crashes	– 6	70	68
Culpable involvements w other veh	– 1	34	33

Table 4-3 estimates the combined effect of ABS and ESC on all police-reported crashes: an overall crash reduction of 14 percent in passenger cars and 17 percent in LTVs.

TABLE 4-3

COMBINED EFFECT OF FOUR-WHEEL ABS AND ESC ON ALL CRASHES

	Percent Reduction of Fatal Involvements		
	Four-Wheel ABS	ESC	Combined
Passenger cars			
All crash involvements	6	8	14
All run-off-road crashes	– 1	45	44
Culpable involvements w other veh	17	13	28
LTVs			
All crash involvements	8	10	17
All run-off-road crashes	11	72	75
Culpable involvements w other veh	20	16	33

The combination is quite effective in preventing both run-off-road crashes and culpable involvements with other vehicles. In fact, the capabilities of ABS and ESC dovetail, for ABS is especially effective in the multi-vehicle crashes and ESC in the single-vehicle crashes.

4.4 Long-term benefits and costs of four-wheel ABS

This report concludes that four-wheel ABS has essentially zero net effect on fatal crashes, but significantly reduces nonfatal crash involvements. We are now ready to tackle the last evaluation question set out in Section 1.8, namely: does ABS prevent enough nonfatal injuries and property damage to endorse ABS technology for its safety benefits just in the nonfatal crashes? For example, NHTSA's evaluations of center high-mounted stop lamps, side marker lamps, and head restraints showed little or no effect on fatalities but significant reductions of property damage and/or nonfatal injuries.[76]

Because ABS is not officially a regulatory requirement, the question will be addressed by an informal order-of-magnitude assessment of benefits and costs rather than a detailed economic analysis. According to Table 4-1, ABS reduces the overall risk of being involved in a crash by 6 percent for passenger cars and 8 percent for LTVs. Given that sales of cars and LTVs are fairly similar, let us assume an overall average 7 percent reduction of crash involvements. The net effect on fatal crashes is close to zero, but the analysis in Section 3.1.7 showed that the effect on crashes involving at least one nonfatal injury was approximately the same as the effect on all crashes.

NHTSA's analysis of the economic impact of motor vehicle crashes in 2000 estimated that the total economic cost was $231 billion in that year.[77] Economic costs include medical and emergency treatment, lost productivity, insurance administration and legal costs, travel delay, and property damage. Of that amount, $60 billion was incurred in property-damage-only crashes, the remainder in crashes that resulted in fatal or nonfatal injury to at least one person. This remainder was allocated according to the maximum injury level, on the Abbreviated Injury Scale (AIS),[78] of the people involved in the crashes; $5 billion was allocated to uninjured people involved in these crashes (AIS 0), $49 billion to people with minor injuries (AIS 1), and $117 billion to people with non-minor (AIS 2 to 5) or fatal injuries.

For this informal analysis, let us conservatively assume that ABS effectiveness is close to zero not only for the fatalities but also for the nonfatal injuries that are not minor (AIS 2 to 5). The sum of the economic cost of crashes with property damage only ($60 billion), or for people with no injury ($5 billion) or minor injury ($49 billion) was $114 billion in 2000. Based on the gross domestic product (GDP) deflator computed by the Bureau of Economic Analysis,[79] which had index value 100 in 2000 and 116.676 in 2006, the economic impact in 2000 would have amounted to $133 billion in 2006 dollars. If ABS reduces these crashes by 7 percent, that

[76] Kahane (2004), pp. 34-41 and 53-58.
[77] Blincoe, L., et al. (2002). *The Economic Impact of Motor Vehicle Crashes, 2000*. NHTSA Technical Report. DOT HS 809 446. Washington, DC: National Highway Traffic Safety Administration.
[78] *The Abbreviated Injury Scale (AIS) - 1990 Revision,* (1990). Des Plaines, IL: American Association for Automotive Medicine,
[79] Bureau of Economic Analyses, *Gross Domestic Product, Percent Change from Preceding Period*, http://www.bea.gov/national/index.htm, http://www.bea.gov/national/xls/gdplev.xls.

amounts to an aggregate economic benefit of $9.3 billion, in 2006 dollars, accruing over the life of the vehicle. That aggregate total, however, overstates the net present value because benefits in future years are not discounted to present value.

As stated above, safety benefits can occur at any time during the vehicle's lifetime. The agency assumes that the distribution of weighted yearly VMT is an appropriate proxy measure for the distribution of crashes over the vehicle's lifetime – and for the distribution of benefits (crashes avoided). This measure takes into account both vehicle survival rates and changes over time in annual average VMT. The Office of Management and Budget's guidelines are to examine both a 3 percent and a 7 percent discount factor to determine the present value of future benefits, by putting them on a comparable basis to costs, which are incurred at the time of purchase. Multiplying the percent of a vehicle's total lifetime mileage that occurs in each year by the discount factor and summing these percentages over the years of the vehicle's operating life results in an average factor for passenger cars and LTVs of 0.8163 at a 3 percent discount rate. For the 7 percent discount rate, the factor is 0.6502. At a 3 percent discount rate, the present value of the benefit would be $7.6 billion ($9.3*0.8163). At a 7 percent discount rate, the present value of the benefit would be $6.0 billion ($9.3*0.6502).[80]

In 2006, a NHTSA contractor estimated the purchase-price increase added to passenger cars and LTVs by ABS, ESC, and traction control systems, based on detailed inspection and disassembly of the brake systems in 11 makes and models of MY 2004 to 2006.[81] The purchase-price increase includes the materials, labor, tooling, and variable burden needed to produce the parts and assemble them into the vehicle, plus mark-ups by the parts suppliers (where applicable), the auto manufacturers, and dealers.[82] The cost analysis differentiated between the basic price increase of just adding ABS to a vehicle and the supplemental cost of also adding ESC and/or traction control systems. The basic price increase for ABS averaged $381.85, in 2006 dollars.[83] This may be considered the long-term cost of ABS per vehicle. It is a considerable savings from the cost of early ABS systems in five cars of MY 1988 to 1990, which averaged $597.56, in 2002 dollars.[84] It is not unusual for unit costs of safety equipment to drop substantially from initial levels, as manufacturers find more efficient ways to produce it.

Vehicle sales in the United States averaged 17 million per year from 2003 to 2007.[85] At $381.85 per vehicle, that amounts to an annual cost of $6.5 billion for ABS, in 2006 dollars. The conservative annual economic benefit of $6.0 to $7.6 billion, computed above, is comparable to an annual cost of $6.5 billion. This informal analysis does not include some additional costs such as the fuel penalty associated with the additional weight of ABS or the repair and

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[80] For derivation of these discount multipliers, see *Vehicle Survivability and Travel Mileage Schedules*, NHTSA Docket No. NHTSA-2005-22223-2218, 2006.
[81] Ludtke, N. F., Osen, W., Gladstone, R., & Lieberman, W. (2006). *Cost and Weight Analysis of the Combined System of Electronic Stability Control (ESC), Antilock Braking System (ABS), and Traction Control System (TCS).* NHTSA Technical Report. DOT HS 810 655. Washington, DC: National Highway Traffic Safety Administration.
[82] Tarbet, M. J. (2004). *Cost and Weight Added by the Federal Motor Vehicle Safety Standards for Model Years 1968-2001 in Passenger Cars and Light Trucks*. NHTSA Technical Report. DOT HS 809 834. Washington, DC: National Highway Traffic Safety Administration.
[83] Ludtke et al., p. iii.
[84] Tarbet, p. 26.
[85] *Ward's Automotive Yearbook 2008*, p. 248.

maintenance costs for ABS. Nevertheless, it shows that, even without any lives saved by ABS, its economic benefits in damage and injuries avoided are at least equivalent to the costs of ABS.

REFERENCES

The Abbreviated Injury Scale (AIS) - 1990 Revision. (1990). Des Plaines, IL: American Association for Automotive Medicine.

Allen, K., Dang, J. N., Doyle, C. T., Kahane, C. J., Roth, J. R., & Walz, M. C. (2008). *Evaluation Program Plan, 2008-2012*. NHTSA Technical Report. DOT HS 810 983.Washington, DC: National Highway Traffic Safety Administration.

Arehart, C., Radlinski, R., & Hiltner, E. (1992). *Light Vehicle ABS Performance Evaluation – Phase II*. NHTSA Technical Report. DOT HS 807 924. Washington, DC: National Highway Traffic Safety Administration.

Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., & Spicer, R. (2002). *The Economic Impact of Motor Vehicle Crashes, 2000*. NHTSA Technical Report. DOT HS 809 446. Washington, DC: National Highway Traffic Safety Administration.

Bureau of Economic Analyses. *Gross Domestic Product, Percent Change from Preceding Period*. http://www.bea.gov/national/index.htm, http://www.bea.gov/national/xls/gdplev.xls.

Collision and Property Damage Liability Losses of Passenger Cars With and Without Antilock Brakes. (1994). Insurance Special Report No. A-41. Arlington, VA: Highway Loss Data Institute.

Dang, J. N. (2004). *Preliminary Results Analyzing the Effectiveness of Electronic Stability Control (ESC) Systems.* NHTSA Evaluation Note. DOT HS 809 790. Washington, DC: National Highway Traffic Safety Administration.

Dang, J. N. (2007). *Statistical Analysis of the Effectiveness of Electronic Stability Control (ESC) Systems – Final Report*. NHTSA Technical Report. DOT HS 810 794. Washington, DC: National Highway Traffic Safety Administration.

Farmer, C. M. (2001). "New Evidence Concerning Fatal Crashes of Passenger Vehicles Before and After Adding Antilock Braking Systems," *Accident Analysis and Prevention, 33*, 361-369.

Farmer, C. M., Lund, A. K., Trempel, R. E. and Braver, E. R. (1996). *Fatal Crashes of Passenger Vehicles Before and After Adding Antilock Brake Systems*. Arlington, VA: Insurance Institute for Highway Safety.

Federal Register Notices:

58 (October 4, 1993): 51735, Executive Order 12866 – Regulatory Planning and Review.

59 (January 4, 1994): 281, ANPRM asking for information about the effectiveness and potential benefits of ABS technologies.

61 (July 12, 1996): 36698, ANPRM deferring indefinitely the ABS requirement.

71 (September 18, 2006): 54712, NPRM to require ESC.

72 (April 6, 2007): 17310, Final Rule requiring ESC.

Government Performance and Results Act of 1993. Public Law 103-62, August 3, 1993.

Harless, D. W., & Hoffer, G. E. (2002). The Antilock Braking System Anomaly: A Drinking Driver Problem? *Accident Analysis and Prevention, 34*, 333-341.

Hertz, E. (2000). *Analysis of the Crash Experience of Vehicles Equipped with All Wheel Antilock Braking Systems (ABS) – A Second Update Including Vehicles with Optional ABS*. NHTSA Technical Report. DOT HS 809 144. Washington, DC: National Highway Traffic Safety Administration.

Hertz, E., Hilton, J., & Johnson, D. M. (1995a). *An Analysis of the Crash Experience of Light Trucks Equipped with Antilock Braking Systems*. NHTSA Technical Report. DOT HS 808 278. Washington, DC: National Highway Traffic Safety Administration.

Hertz, E., Hilton, J., & Johnson, D. M. (1995b). *An Analysis of the Crash Experience of Passenger Cars Equipped with Antilock Braking Systems.* NHTSA Technical Report. DOT HS 808 279. Washington, DC: National Highway Traffic Safety Administration.

Hiltner, E., Arehart, C., & Radlinski, R. (1991). *Light Vehicle ABS Performance Evaluation*. NHTSA Technical Report. DOT HS 807 813. Washington, DC: National Highway Traffic Safety Administration.

Intermodal Surface Transportation Efficiency Act of 1991. Public Law 102-240, December 18, 1991.

Kahane, C. J. (1993). *Preliminary Evaluation of the Effectiveness of Rear-Wheel Antilock Brake Systems for Light Trucks*. NHTSA Docket No. 70-27-GR-026. Washington, DC: National Highway Traffic Safety Administration.

Kahane, C. J. (1994). *Preliminary Evaluation of the Effectiveness of Antilock Brake Systems for Passenger Cars*. NHTSA Technical Report. DOT HS 808 206. Washington, DC: National Highway Traffic Safety Administration.

Kahane, C. J. (2004). *Lives Saved by the Federal Motor Vehicle Safety Standards and Other Vehicle Safety Technologies, 1960-2002*. NHTSA Technical Report. DOT HS 809 833. Washington, DC: National Highway Traffic Safety Administration.

Kahane, C. J., & Hertz, E. (1998) *The Long-Term Effectiveness of Center High Mounted Stop Lamps in Passenger Cars and Light Trucks*. NHTSA Technical Report. DOT HS 808 696, Washington, DC: National Highway Traffic Safety Administration.

Kullgren, A., Lie A., & Tingvall, C. (1994). The Effectiveness of ABS in Real Life Accidents, *Proceedings of the Fourteenth International Technical Conference on the Enhanced Safety of*

Vehicles. Paper No. 94-S4-O-07. Washington, DC: National Highway Traffic Safety Administration.

Ludtke, N. F., Osen, W., Gladstone, R., & Lieberman, W. (2006). *Cost and Weight Analysis of the Combined System of Electronic Stability Control (ESC), Antilock Braking System (ABS), and Traction Control System (TCS)*. NHTSA Technical Report. DOT HS 810 655. Washington, DC: National Highway Traffic Safety Administration.

Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users of 2005. Public Law 109-59, August 10, 2005.

Tarbet, M. J. (2004). *Cost and Weight Added by the Federal Motor Vehicle Safety Standards for Model Years 1968-2001 in Passenger Cars and Light Trucks*. NHTSA Technical Report. DOT HS 809 834. Washington, DC: National Highway Traffic Safety Administration.

Vehicle Survivability and Travel Mileage Schedules. (2006). NHTSA Docket No. NHTSA-2005-22223-2218, Washington, DC: National Highway Traffic Safety Administration.

Ward's Automotive Yearbook. Annual publication. Detroit: Ward's Communications.

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